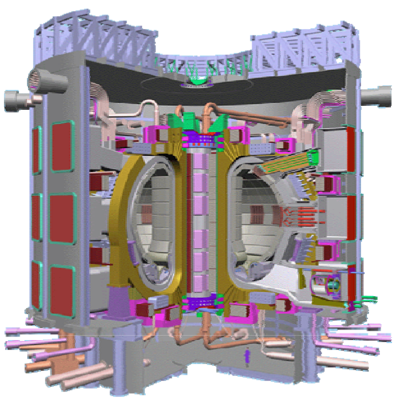
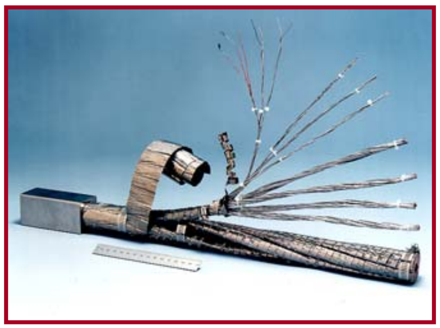
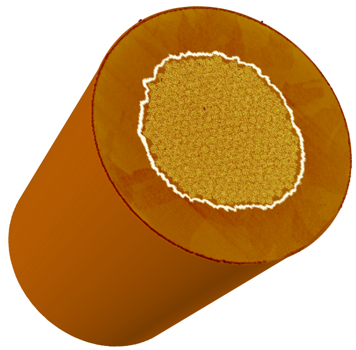
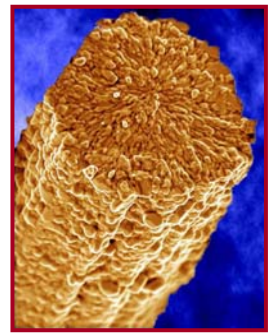
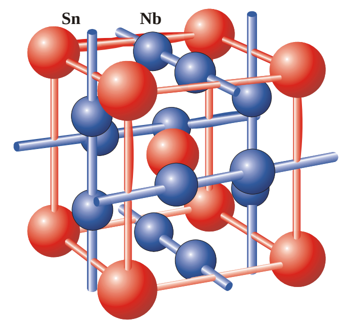
A Synergy of Novel Experiments, Materials Science, Fundamental Physics, and Superconducting Magnets

Arno Godeke

Berkeley, CA

August 15, 2007

15 years in Applied Superconductivity

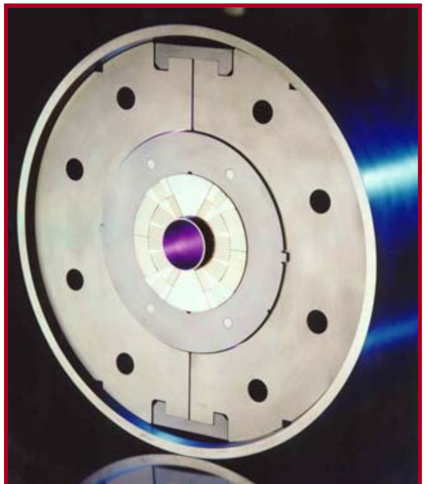
- 1992–1998 University of Twente – Support Engineer
  - Characterization of Nb_3Sn, Bi-2212, Bi-2223, Nb_3Al
- 1998 NHMFL – Sabbatical
  - Development 3 T W&R Bi-2212 insert magnet (in 20 T)
- 1998–2002 University of Twente – Research Engineer
  - Development 1 MVA Bi-2223 resonator, Nb_3Sn research
- 2002–2003 Appl. Supercond. Center – Research Intern
  - Nb_3Sn research
- 2004–2005 University of Twente – Research Associate
  - PhD thesis, MgB_2 research, proposals
- 2006– LBNL – Visiting Physicist Postdoctoral Fellow
  - Bi-2212 W&R magnet technology, Nb_3Sn characterization

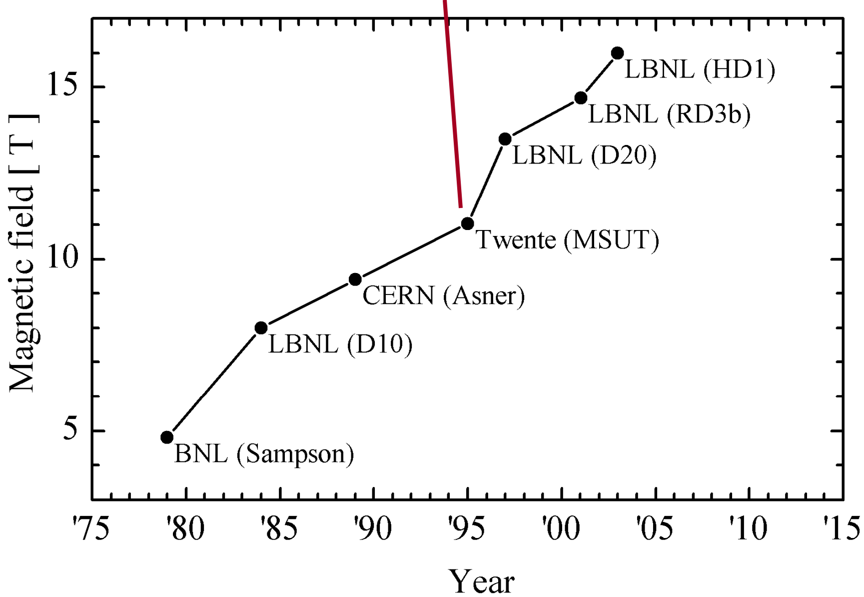
1992 – 1996

Research on Nb_3Sn wires and tapes

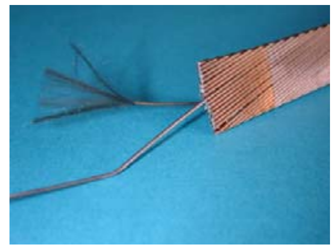
Nb_3Sn research for magnets

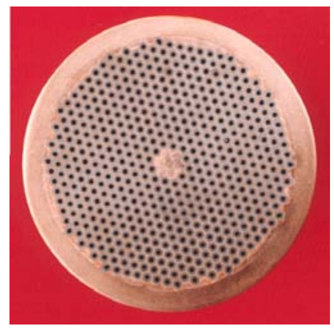
Twente MSUT: 11 T, no training

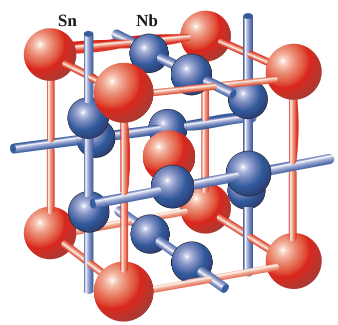




Supporting research





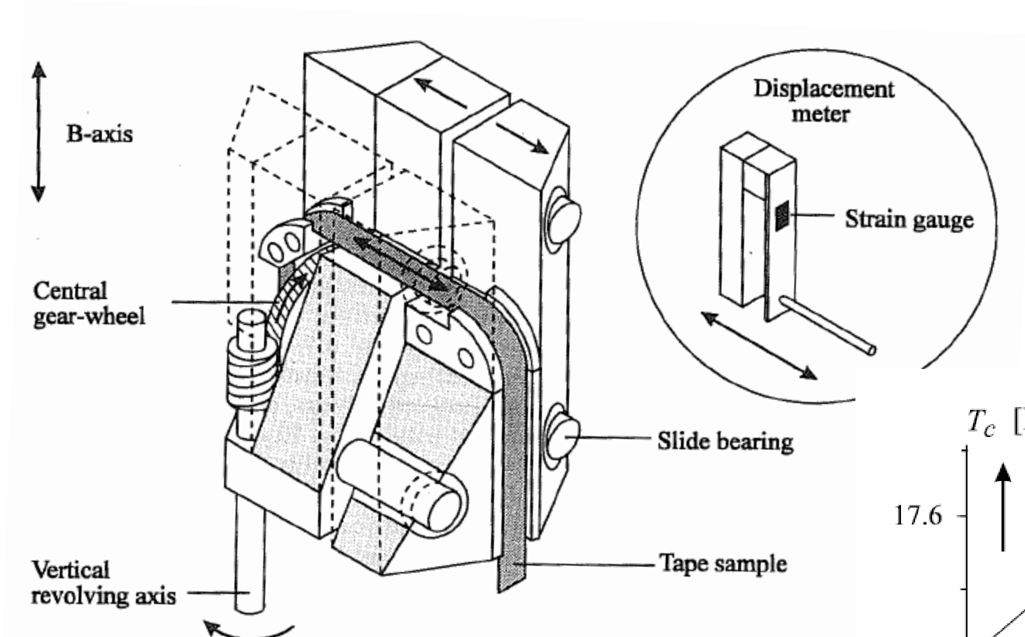


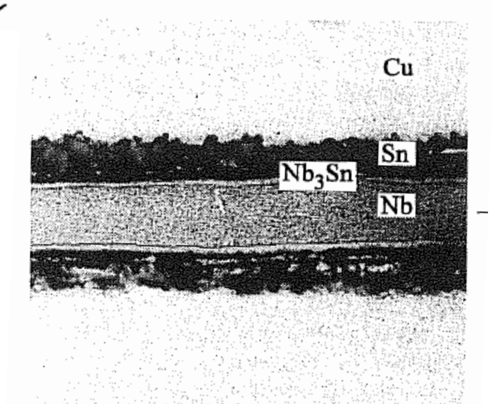
- $J_c(H,F_{\perp})$
  - Cables
- $J_c(H,T,\varepsilon_{axial},F_{\perp})$
  - Wires
  - Tapes
- Fundamental strain
  - Tapes
  - Wires
- Tapes and wires:
  - PhD Ten Haken ‘94

1992: Final work: $J_c(H,T,\varepsilon_{axial})$ tapes

Variable *T* using insulating cup

- A first?

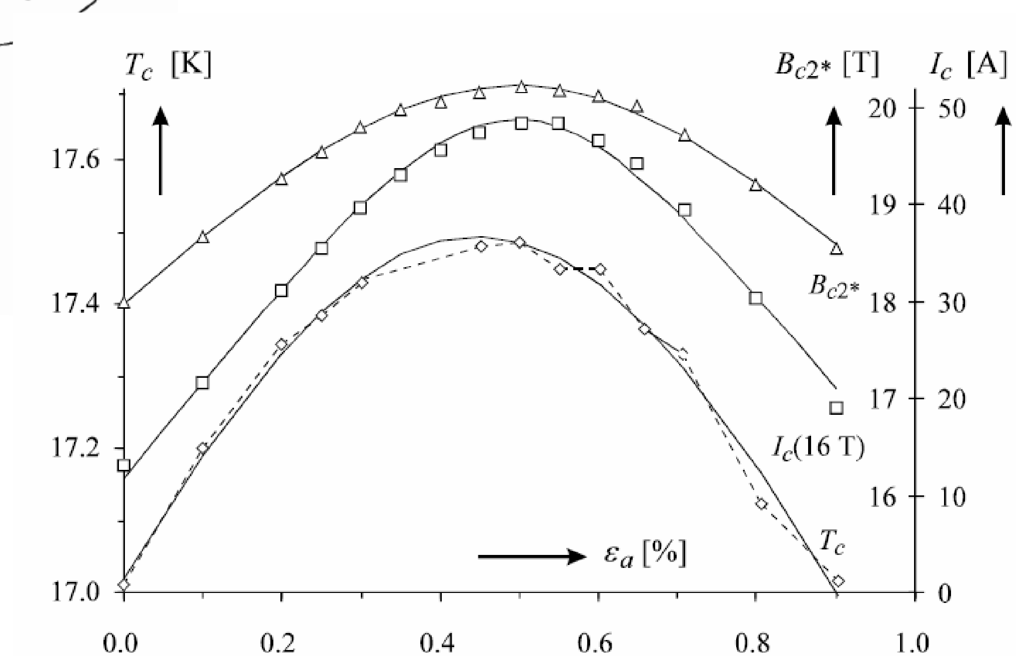




$T_c(\varepsilon_{axial})$ on Nb_3Sn tapes

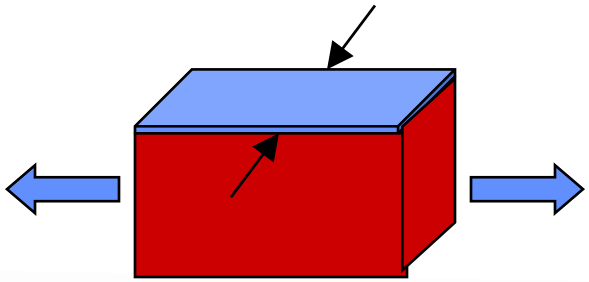
- A first?

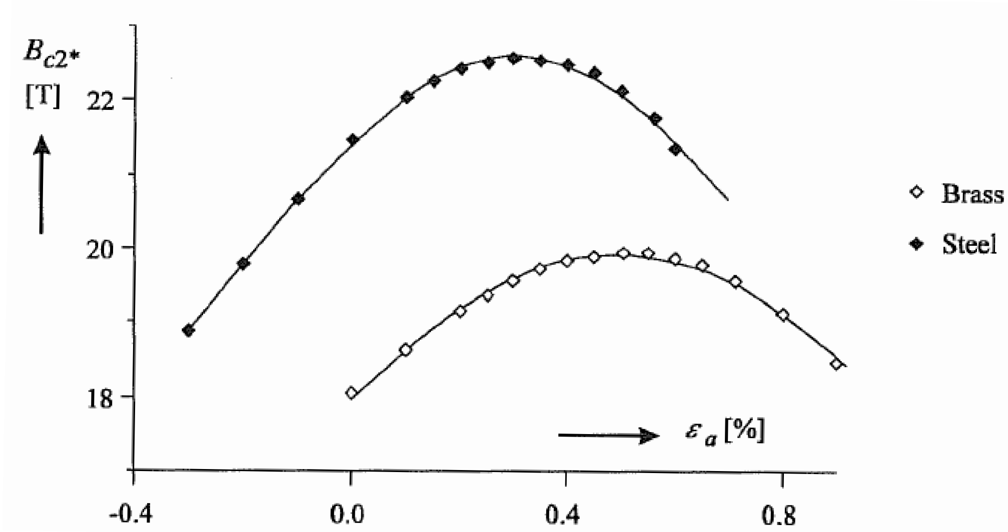
Source:
Ten Haken, *PhD thesis* 1994
Ten Haken, Godeke, Ten Kate, *TAS* 1995
Ten Haken, Godeke, Ten Kate, *ACE* 1997



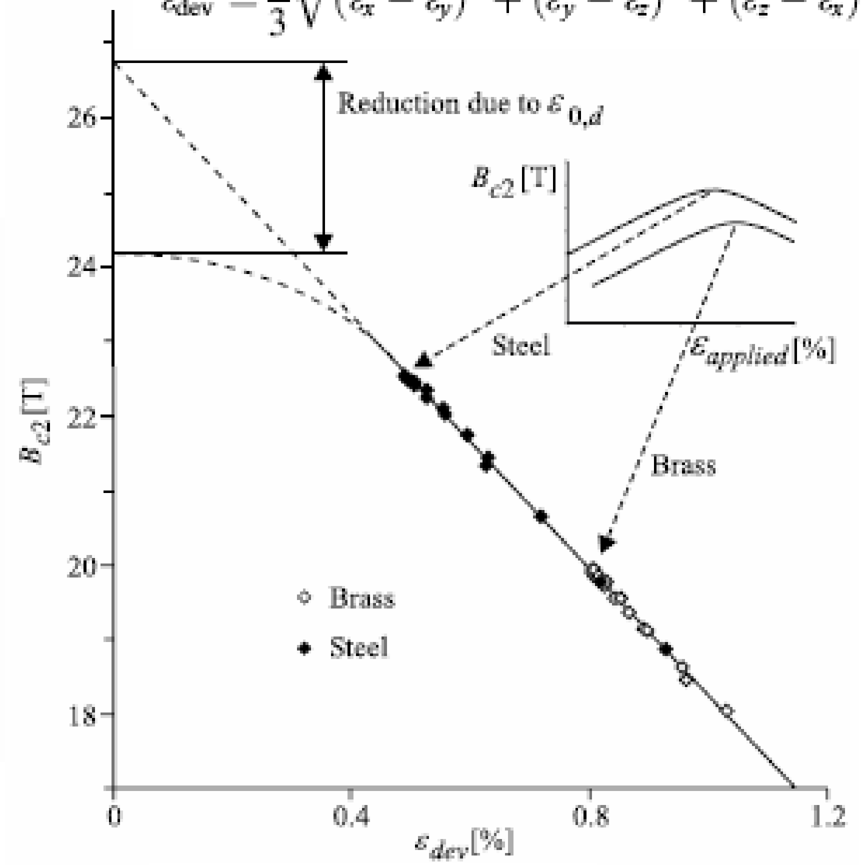
1993: 3D Deviatoric strain model

- A tape on two substrate materials, soldered at RT





$$\varepsilon_{\text{dev}} = \frac{2}{3}\sqrt{(\varepsilon_x - \varepsilon_y)^2 + (\varepsilon_y - \varepsilon_z)^2 + (\varepsilon_z - \varepsilon_x)^2}.$$



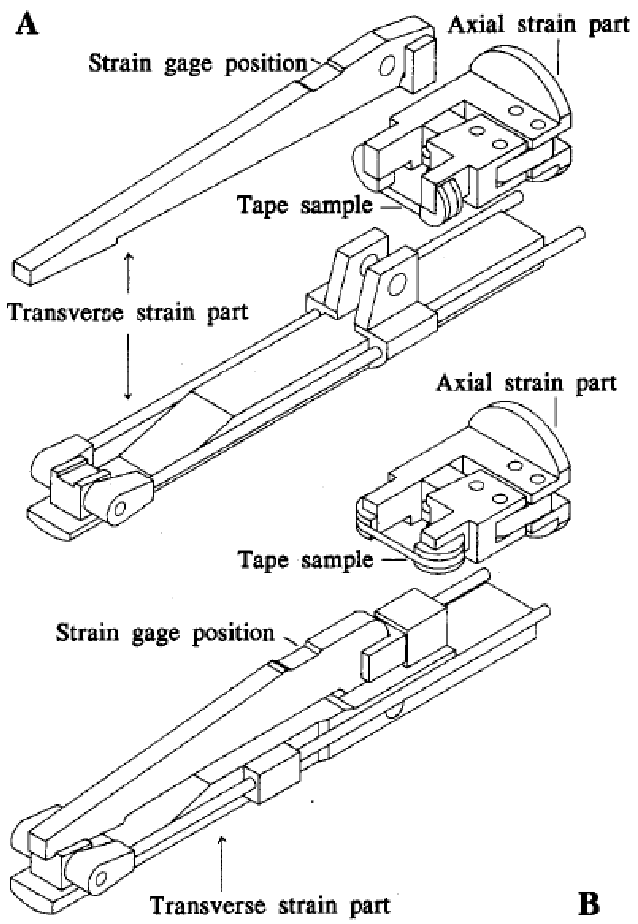
$$B_{c2}(\varepsilon_{\text{dev}}) \approx B_{0,d} - C_d \varepsilon_{\text{dev}}$$

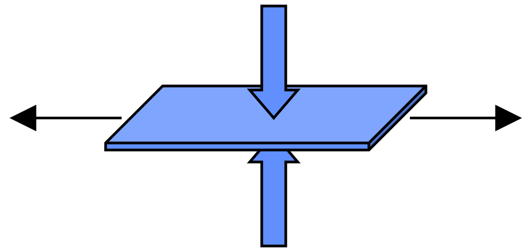
$$B_{c2}(\varepsilon_{\text{dev}}) = B_{0,d} - C_d\sqrt{(\varepsilon_{\text{dev}})^2 + (\varepsilon_{0,d})^2}.$$

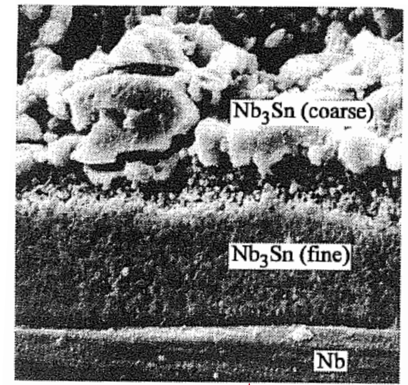
Source:
Ten Haken, *PhD thesis* 1994
Ten Haken, Godeke, Ten Kate, *TAS* 1995
Godeke, Ten Haken, Ten Kate, *Phys. C* 2002

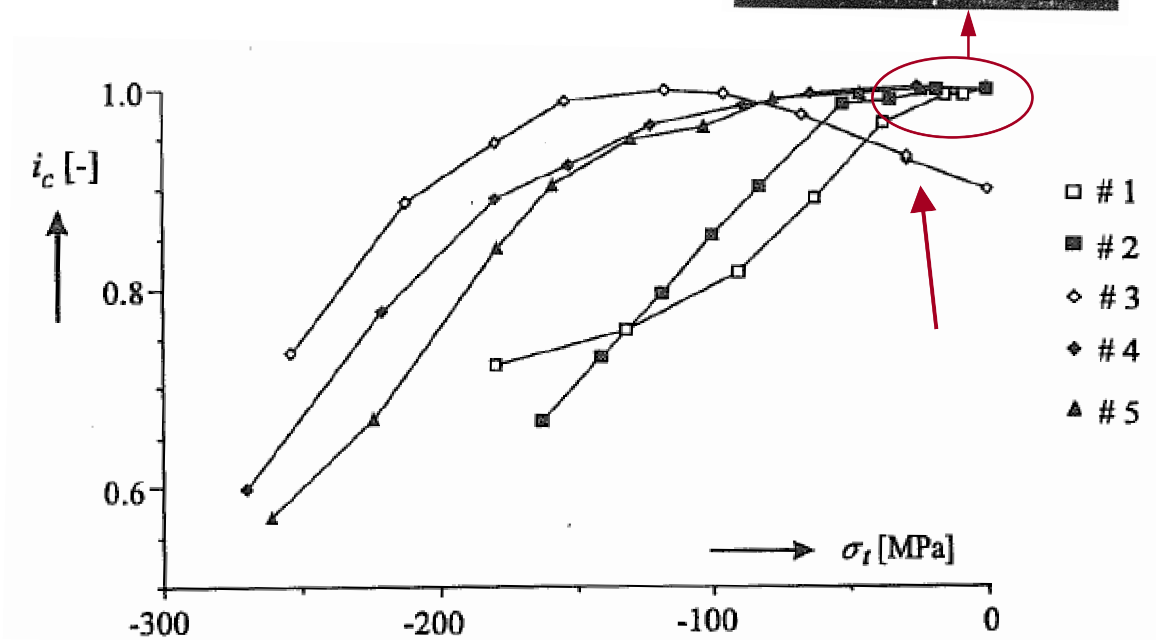
1993: A pressure induced rise in I_c

- Pressing on a tape should initially increase I_c
  - It does.







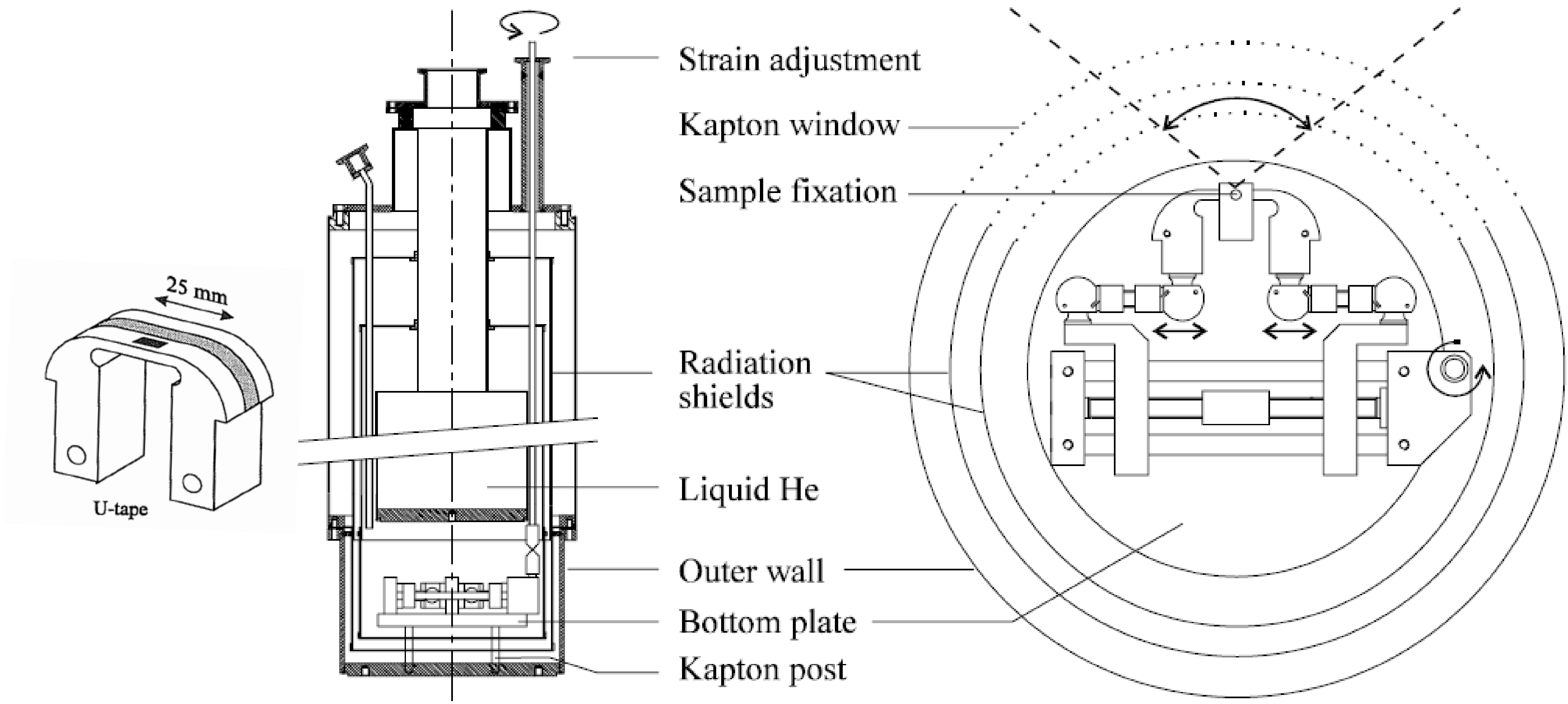


Source:
Ten Haken, *PhD thesis* 1994
Ten Haken, Godeke, Ten Kate, *TAS* 1993

1996: Low temperature X-ray diffraction

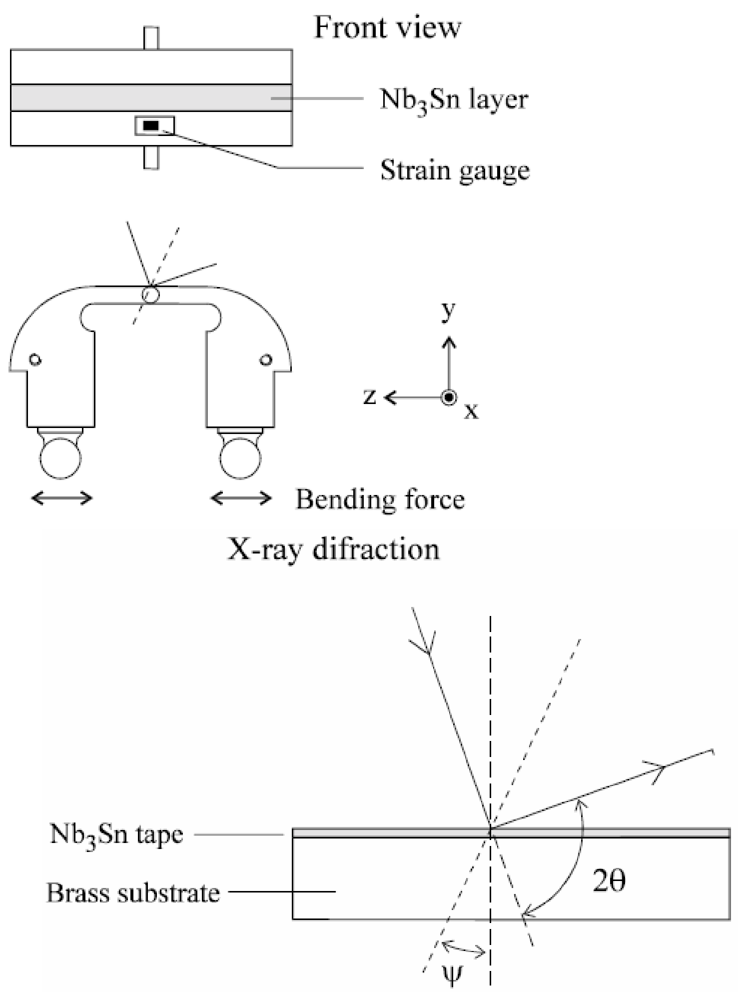
- Is solder strong enough to transfer large strains to the sample?
  - Low temperature x-ray diffraction experiment

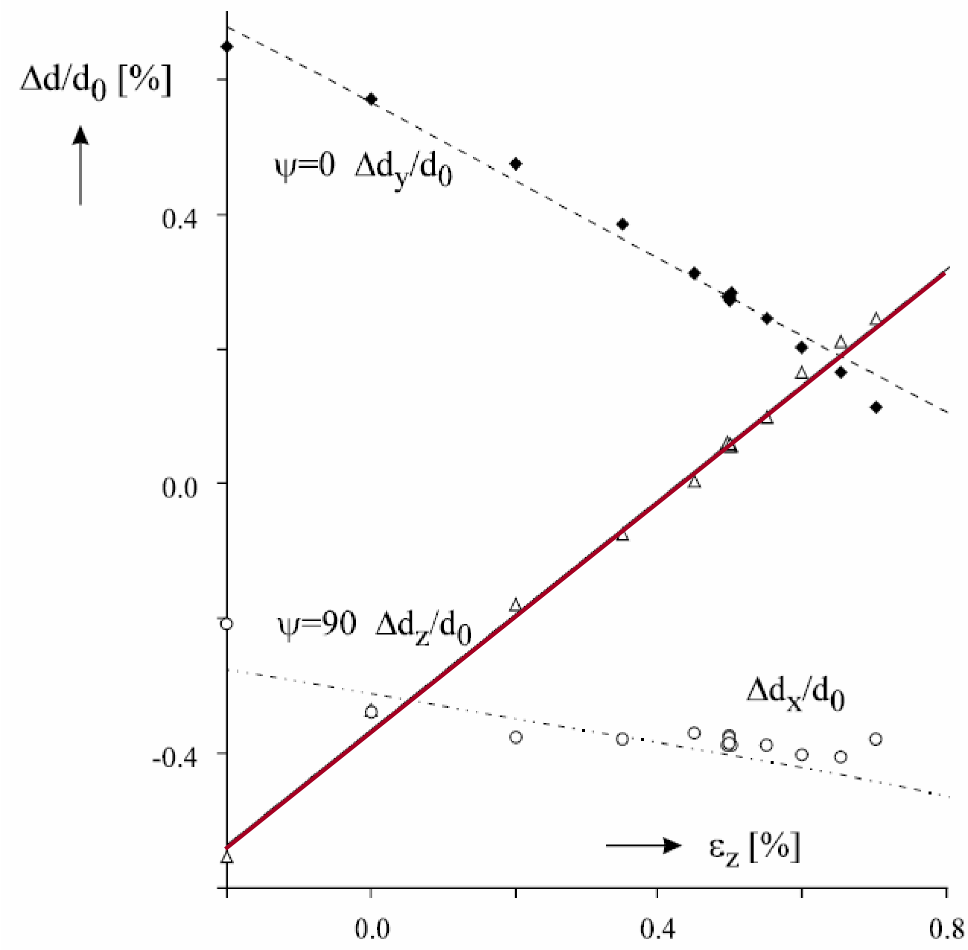
Source: Ten Haken, Godeke, Ten Kate, *ACE* 1997



1996: Low temperature X-ray diffraction

- Is solder strong enough to transfer large strains to the sample?
  - Yes.





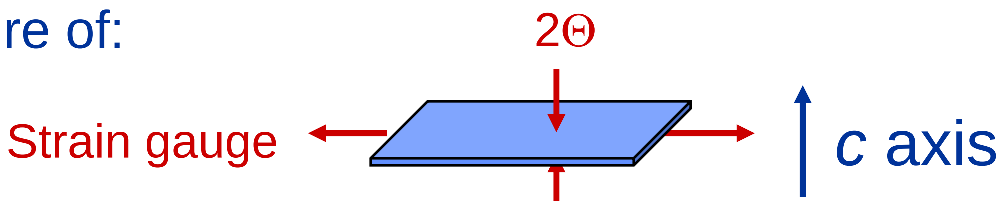
Source: Ten Haken, Godeke, Ten Kate, *ACE* 1997

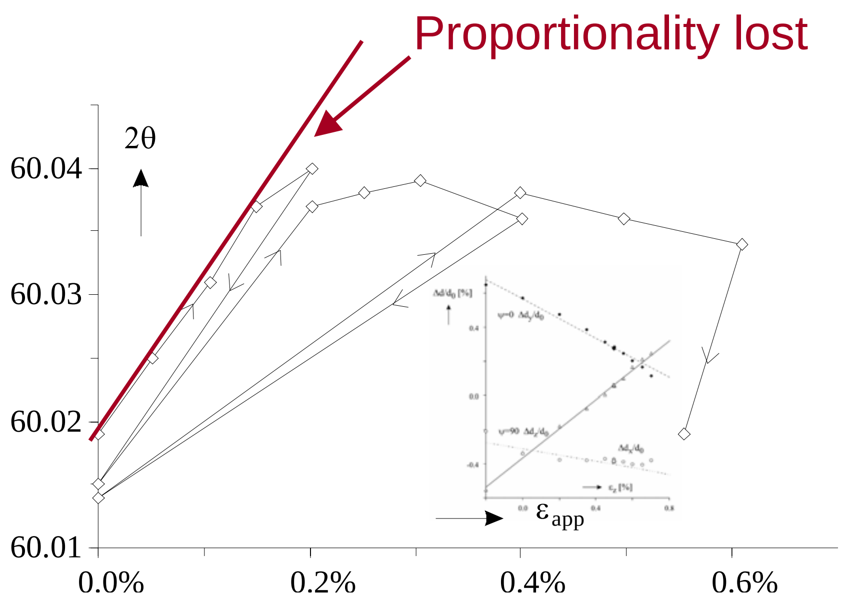
1993 – 1996

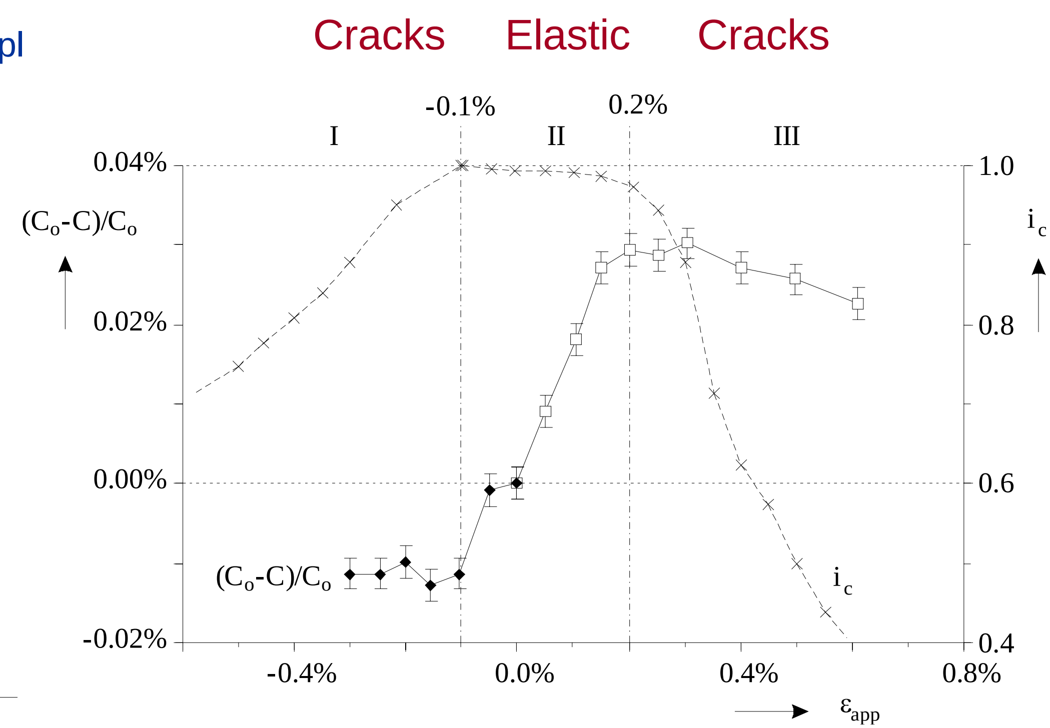
Some key results on Bi-2212 tapes

1996: Crack formation in Bi-2212

- In contrast to Nb_3Sn: Bi-2212
- Shift 2Θ for 0020 peak measure of:
  - Strain in *c* direction
  - $\varepsilon_{c\text{-}direction} = \nu\, \varepsilon_{applied}$
- Only elastic at $i_c(\varepsilon_{applied})$ plateau
  - *c*-axis strain proportional to ε_{appl}



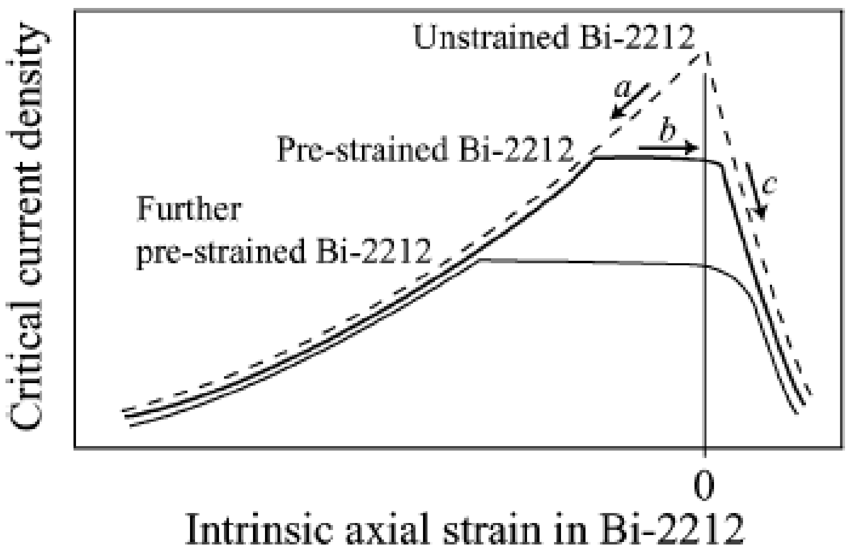




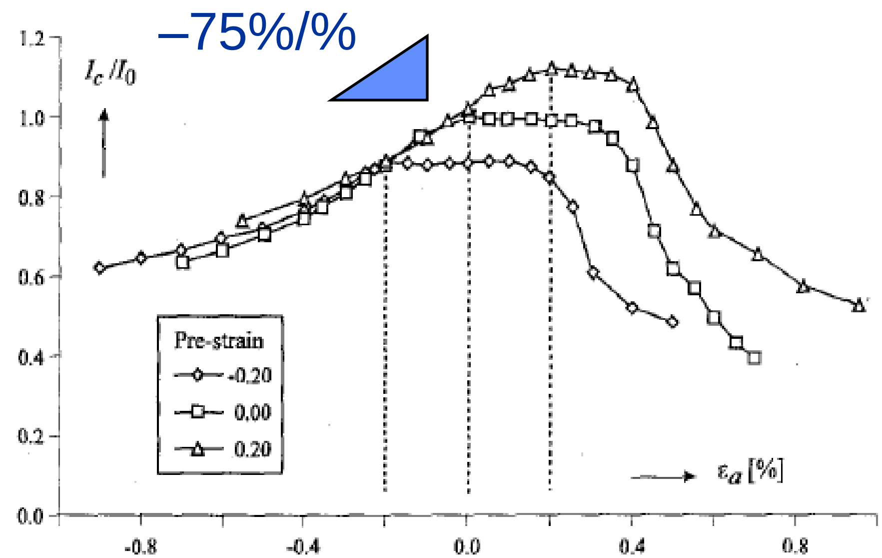
Source: Ten Haken, Ten Kate, *Phys C* 1996

1996: Generalized 2212 behavior: A model

Model…



…and measurement



All axial compressive strain irreversibly reduces J_c due to crack formation

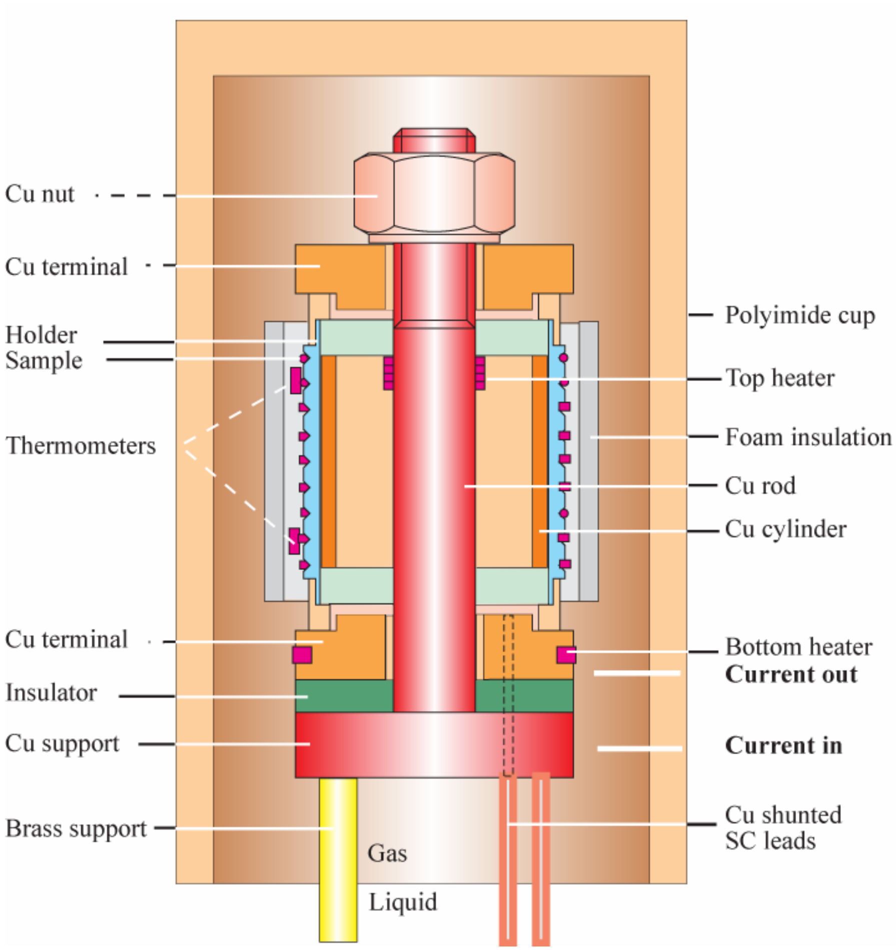
Source: Ten Haken, Godeke, Schuver, Ten Kate, *ToM* 1996

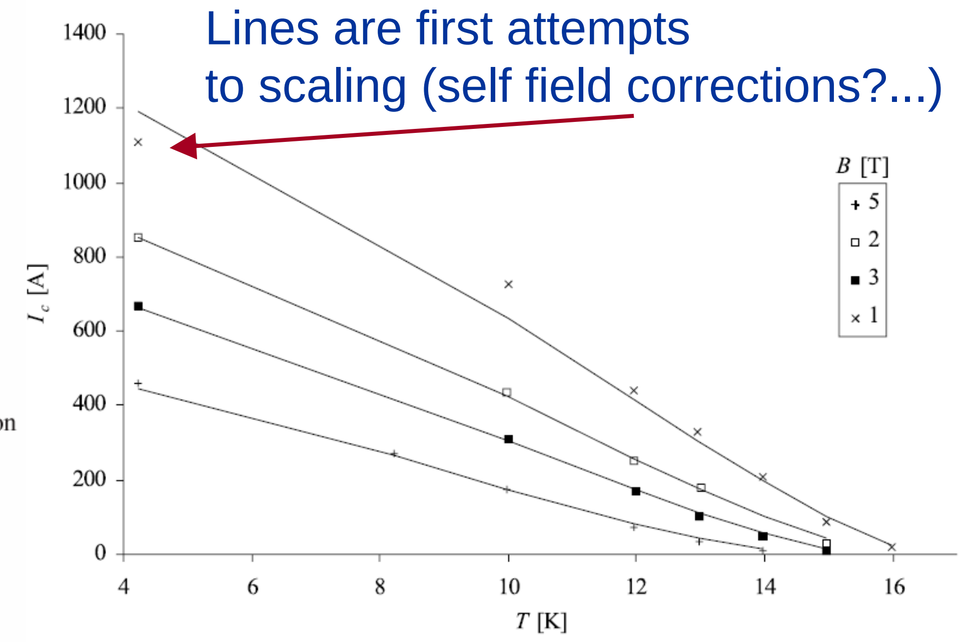
1996 – 1998

$J_c(H,T,\varepsilon_{axial})$ characterizations of Nb_3Sn wires for ITER

1996: $J_c(H,T)$ rig

- At least up to 750 A in He gas
- Quick, accurate PID temperature control (error < 50 mK)



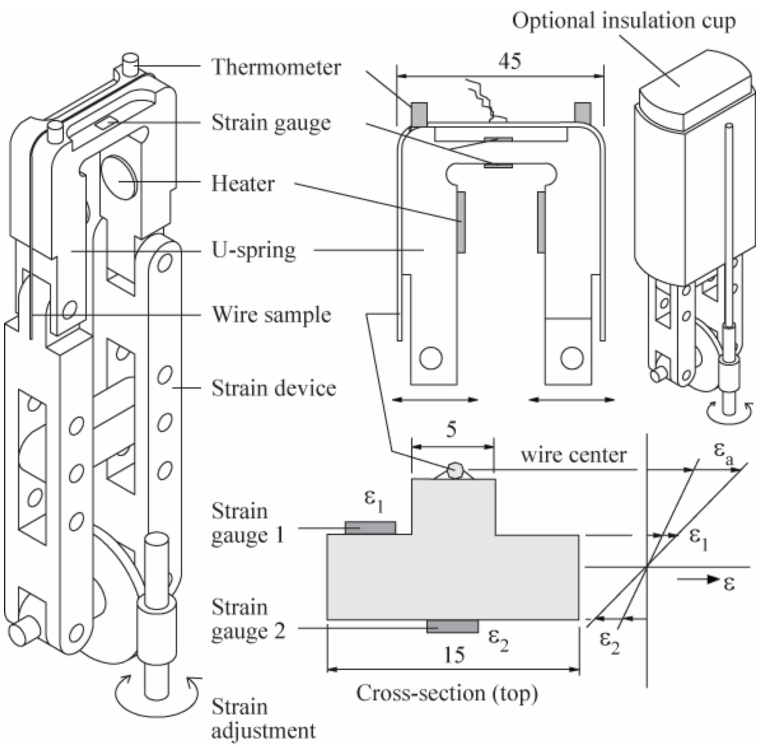


14: *The low field $I_c(T)$ dependence of the VAC sample on the ITER barrel. All lines are calculated with Eq. 12, Table 2 and Table 3.*

Source:
Godeke, et al., *ITER Report* 1998
Godeke, et al., *ITER Report* 2000

1996 – 1997: $J_c(H,T,\varepsilon_{axial})$ rig – A first?

$J_c(H,T,\varepsilon_{axial})$ scaling with deviatoric strain model + improved T-dependence

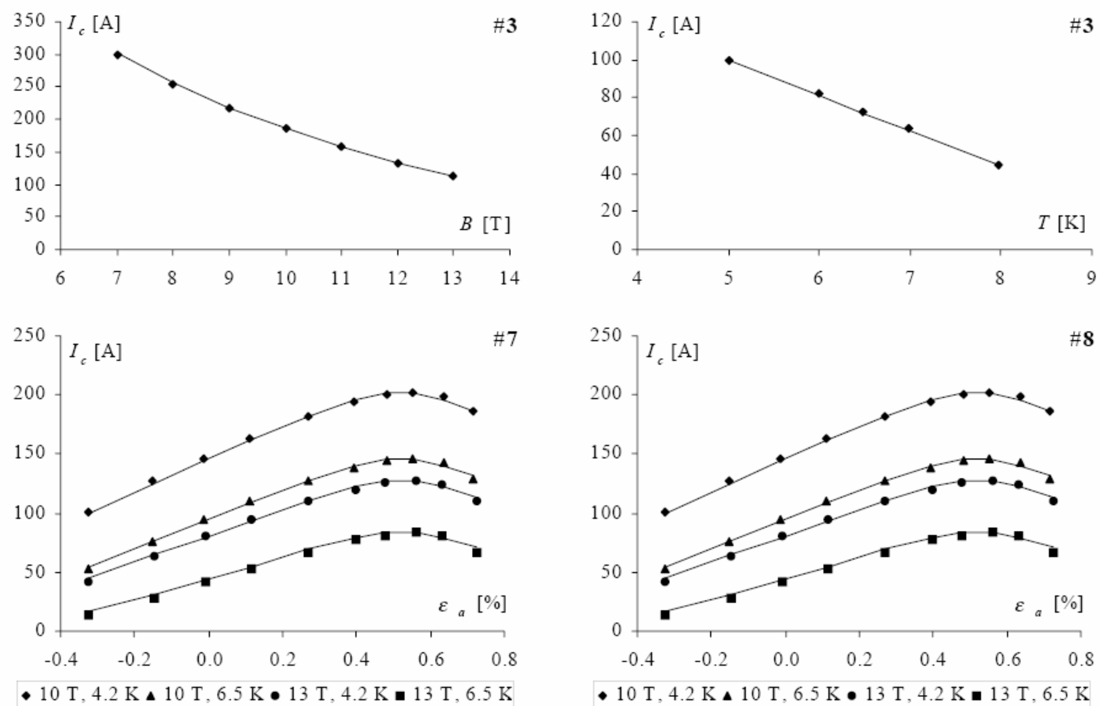


Source:
Godeke, et al., *ITER Report* 1998
Godeke, et al., *ITER Report* 2000
Godeke, Ten Haken, Ten Kate, *TAS* 1999
Ten Haken, Godeke, Ten Kate, *JAP* 1999

Table 10: Sample parameters for the FUR samples.

I_{Cu}	δ_{Ti}	δ_{Brass}	$\varepsilon_{0,a}$	C_a'	B_{c2m}*(0 K)	T_{cm}*(0 T)
1.667	-0.215 %	-0.512 %	0.118 %	38.00	33.28	17.75

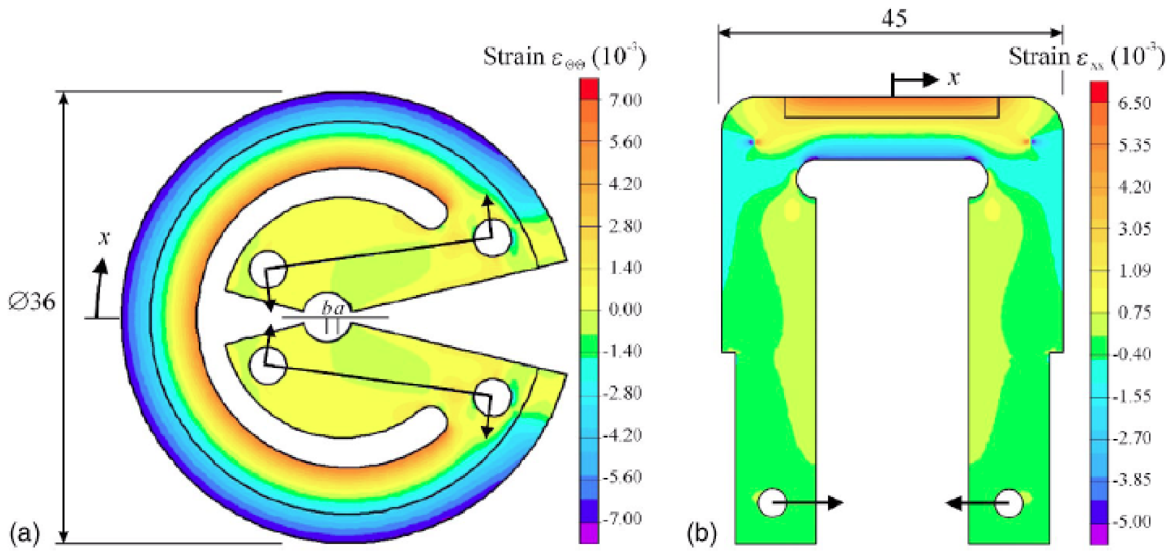
Sample:	C
3, 7, 8	9465

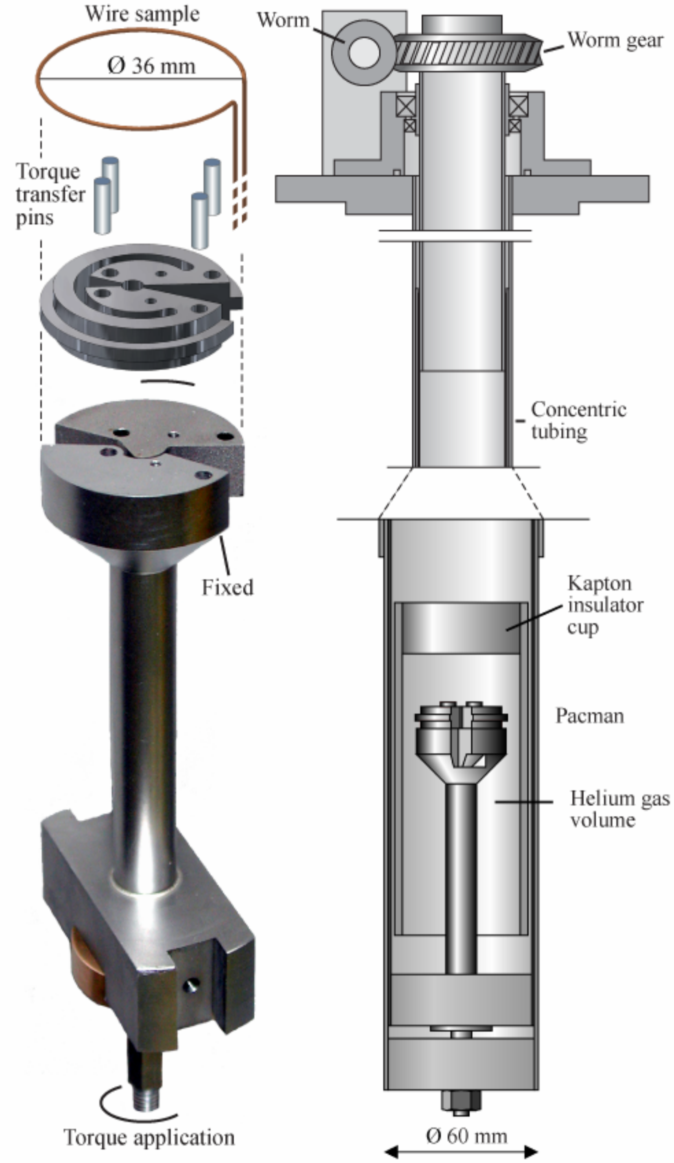


2000 – 2003: Longer length $J_c(H,T,\varepsilon_{axial})$ rig

`Pacman'

- Circular bending beam with >10x available sample length
- Therefore >10x more voltage resolution

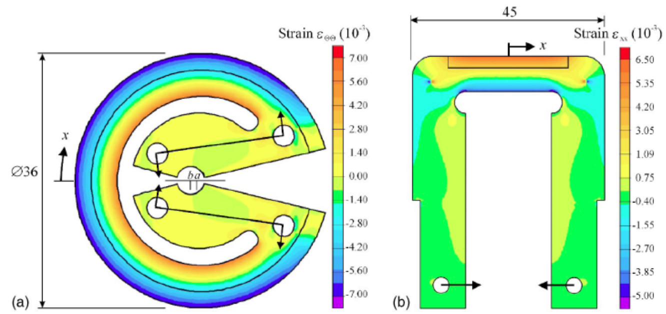


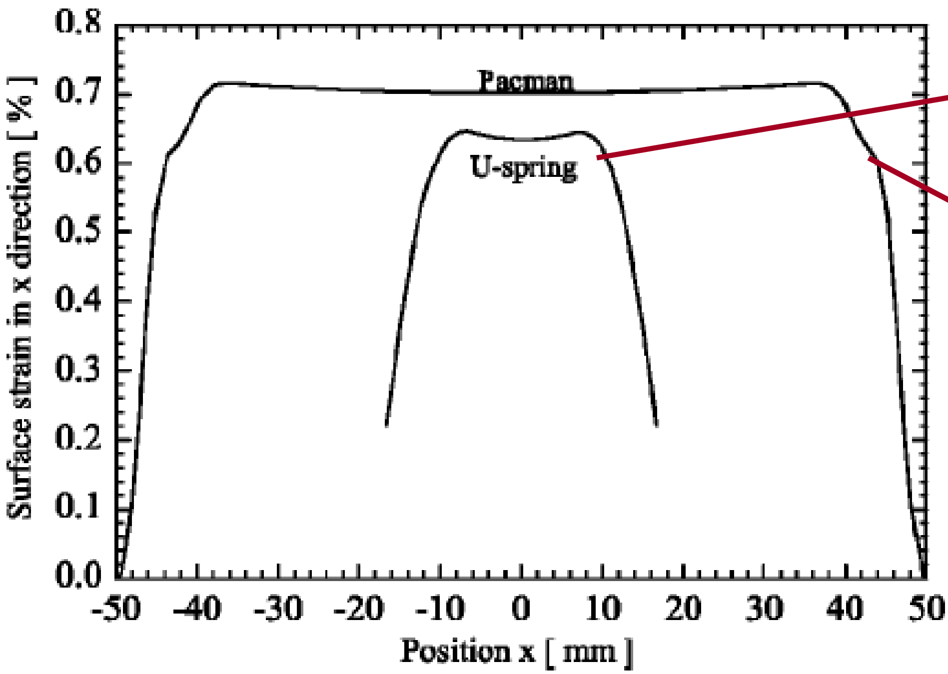


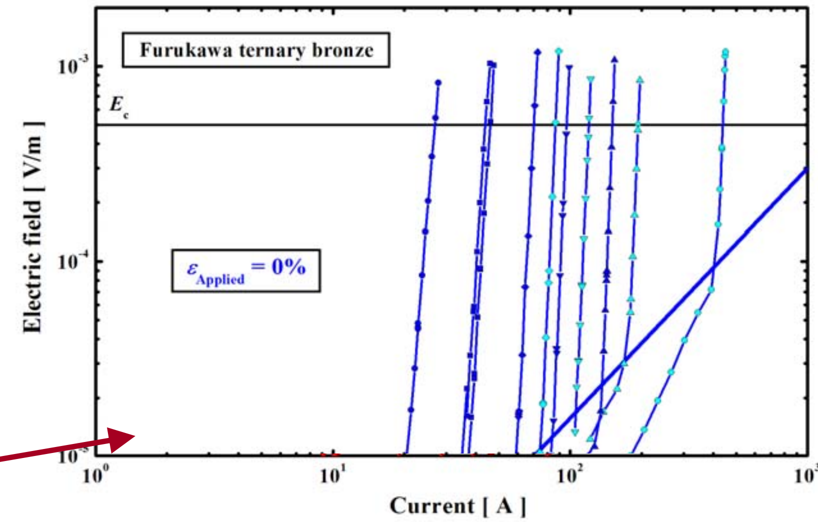
Source:
Godeke, et al., *RSI* 2004

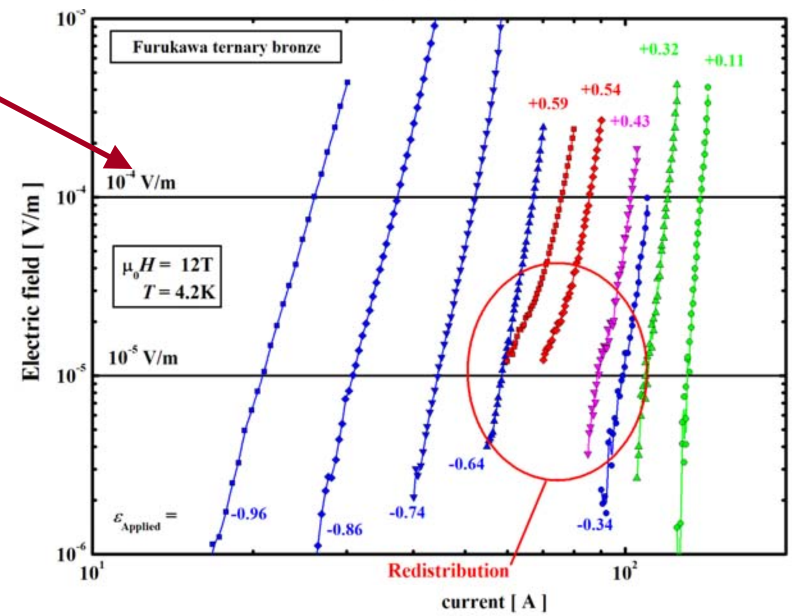
2000 – 2003: Longer length $J_c(H,T,\varepsilon_{axial})$ rig

Longer length for lower voltage criteria









Source:
Godeke, et al., *RSI* 2004

Critical current scaling, Material Science and Fundamental Physics

- Invited Topical Review Superconductor Science and Technology
- Invited Topical Review Cryogenics
- Invited Topical Review Proc. RF Supercond. Workshop
- Topical Review Superconductor Science and Technology
- 1x Superconductor Science and Technology
- 2x Journal of Applied Physics
- 1x Review of Scientific Instruments
- 1x Physica C
- Handful of IEEE proceedings and Adv. Cryog. Eng.
- PhD thesis

- About 170 citations

1998: J_c scaling: Summers does not work

ITER

- ~ 10 wire manufacturers
- Characterized for *H* < 13 T, all *T*, strain -0.8% ⇔ +0.4%

Summers scaling wrong

- Improvement step 1
  - Ekin Power Law replaced by deviatoric strain model
  - Enables 3D strain scaling

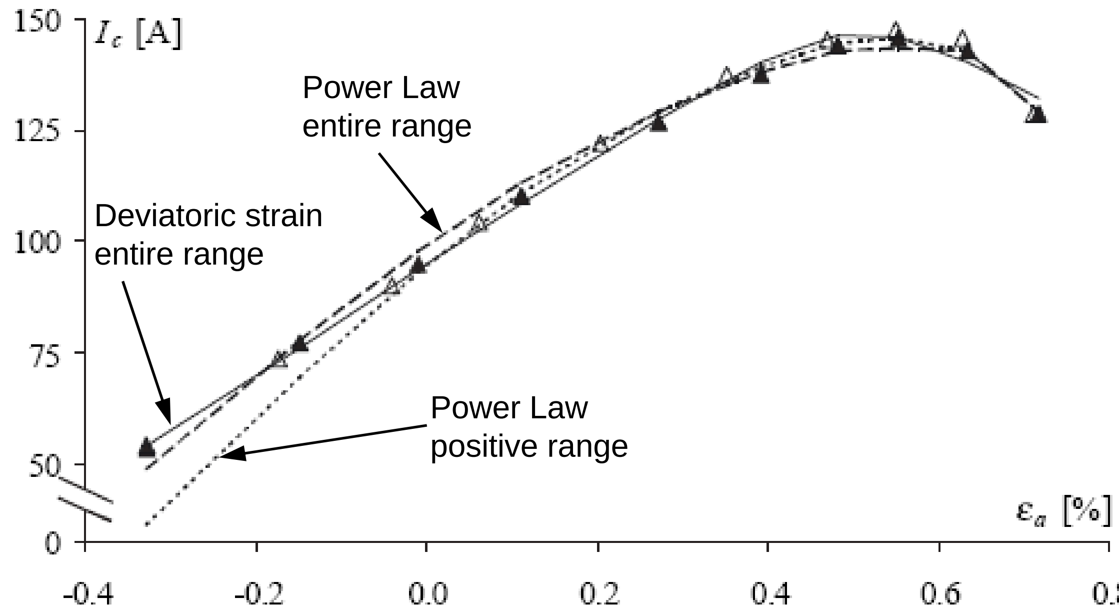


Figure 1: The critical current versus applied strain for conductor A, at $B = 10$ T and $T = 6.5$ K. The other combinations of field and temperature show similar behavior. The lines are described in the text.

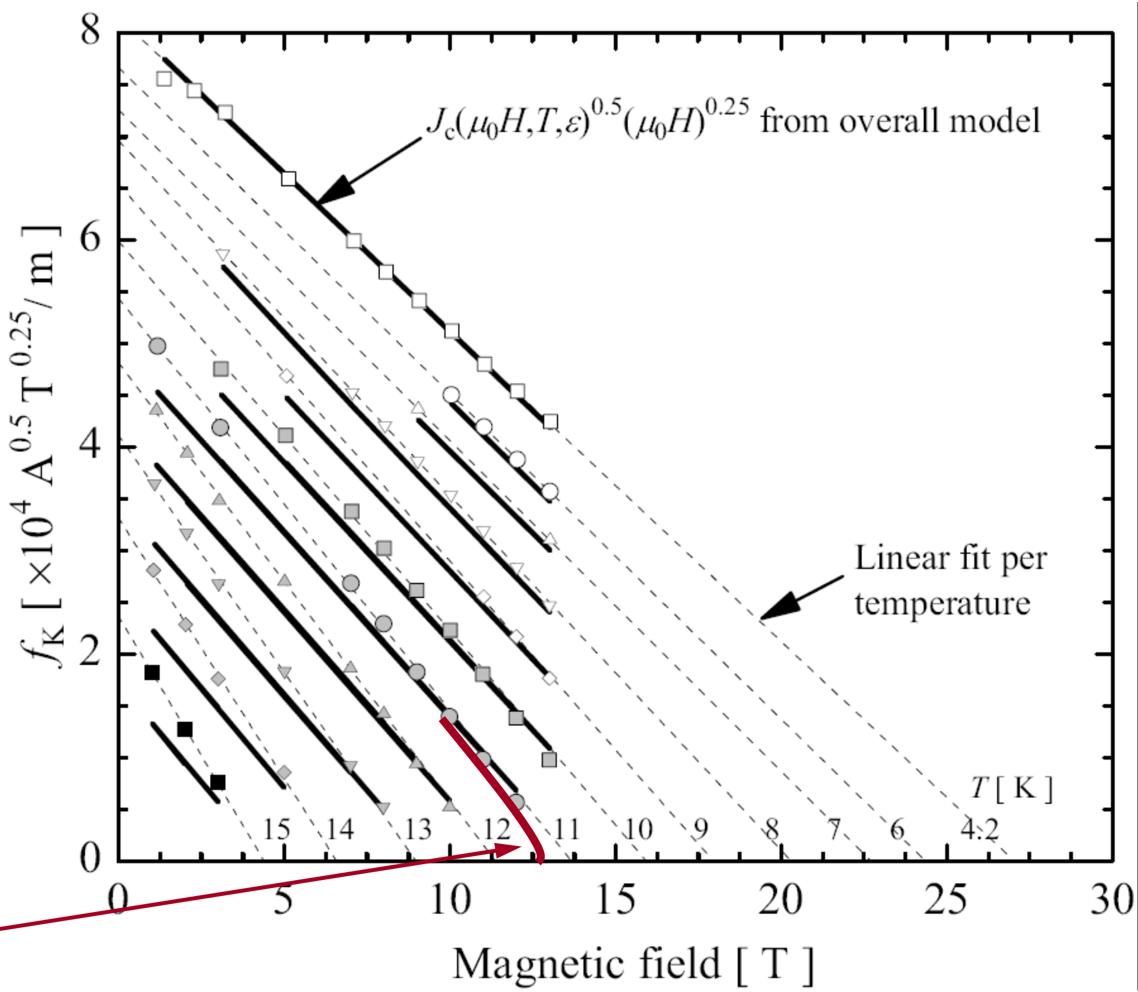
1998: J_c scaling: Summers does not work

Summers scaling: 'Kramer plot' example ($J_c^{0.5}B^{0.25}$ = linear)

- Incorrect *T* dependence
  - *T* dependence is $H_{c2}^*(T)$, $\kappa(T)$, and two powers

$$F_p(H,T) \cong C \frac{[\mu_0 H_{c2}(T)]^\nu}{\kappa_1(T)^\gamma} f(h)$$

- The powers are clearly wrong
  - Why?
- Kramer plots exhibit tails
  - Why?

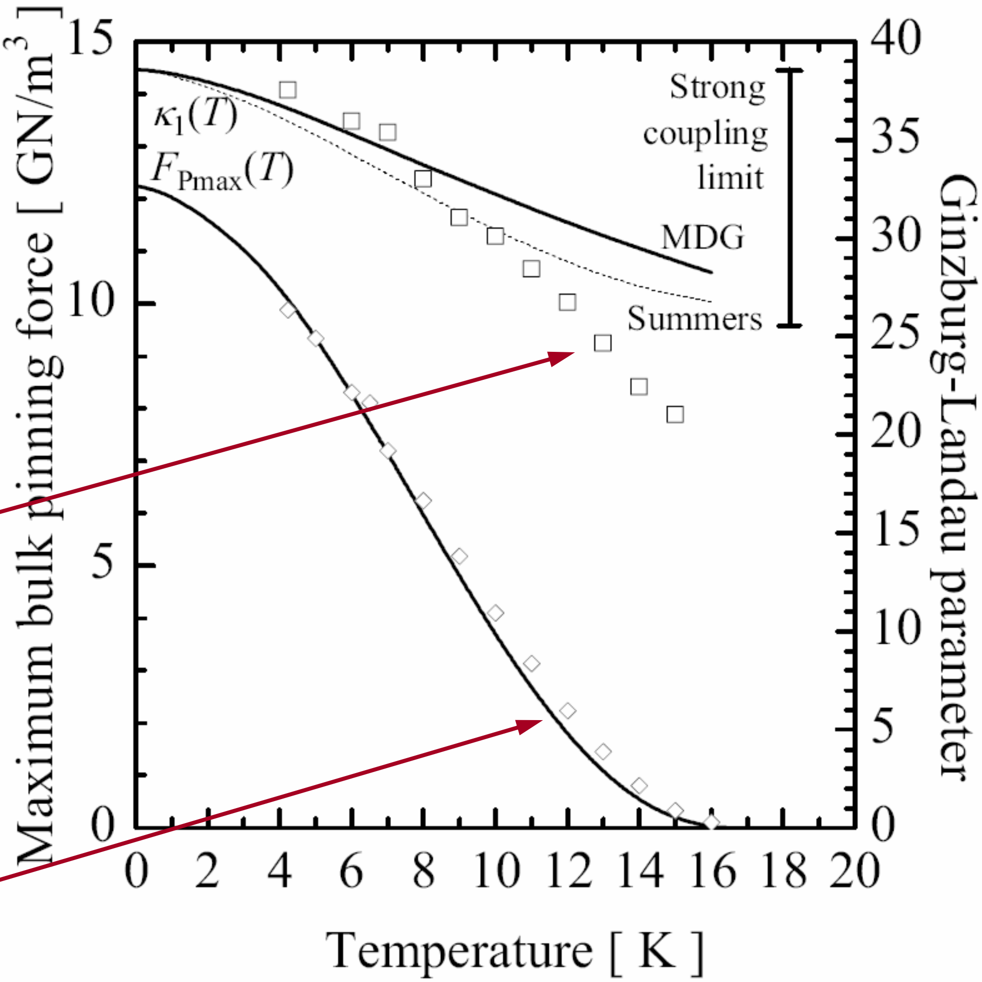


2004: J_c scaling: Summers does not work

- Summers defined T dependence by fitting $\kappa(T)$

$$\frac{H_{c2}(T)}{H_{c2}(0)} = \left(1 - \underbrace{t^2}_{H_c(T)}\right)\frac{\kappa_1(T)}{\kappa_1(0)}$$
$$= \left(1-t^2\right)\left[1-0.31t^2\left(1-1.77\ln t\right)\right]$$

- But…
  - $\kappa(T)/\kappa(0) > 1.5$
  - Conflicts with strong coupling limit
  - Physically incorrect
- Also $H_{c2}^*(T)$ is clearly wrong
  - Why?

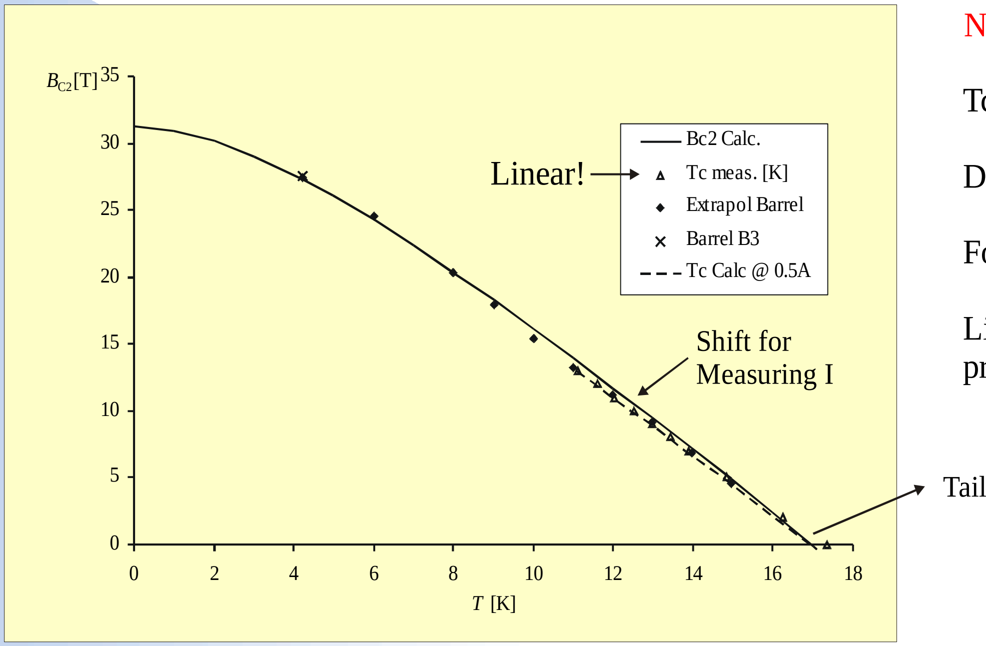


2001: J_c scaling: Peculiarities in $H_{c2}(T)$

Why the Summers relations can and should be improved upon

University of Twente

Ic(T) => ITER data post B3 measurements in Twente:



Needed:

Tc(B) at known current

Delivers Tc(B)<=>Bc2(T)

Followed by:

Linear description, preferably fundamental

Important:
Correction for measuring current

	I = 1 A	I = 0.5 A	I = 0.05 A	I = 0.005 A	I = 0 A
T_c @ B=10T	12.34 K	12.46 K	12.66 K	**12.72 K**	**12.74 K**
B_{c2} @ T=10K	14.97 T	15.30 T	15.85 T	**16.03 T**	**16.11 T**

A. Godeke February 2001

A short side track related to ITER model coils…

Characterization of pre-strain and multi-dimensional deformation influences on strands and sub-cables

University of Twente

<u>CSMC and CS insert results => Complications:</u>

- Initial degradation? => Which *pre-strain*?
  => Which *initial Ic*?
- Degradation Tcs @ cyclic testing => Lorentz forces?
- From barrel data to cable level:
  - => Inconsistency barrel data between institutions
  - => Derived critical parameters depend on interpretation
  - => Uncertainty due to:
    - => Current re-distribution effects
    - => Self-field effects
    - => E-level

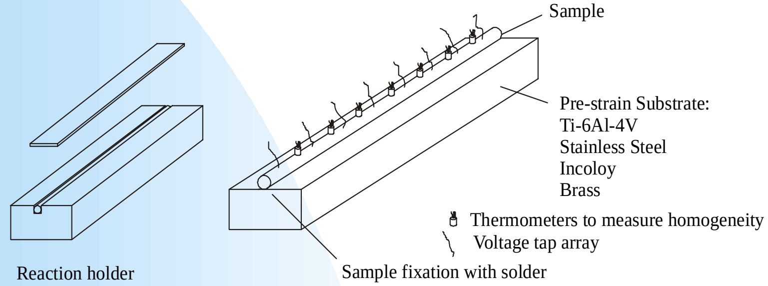
A. Godeke January 2001

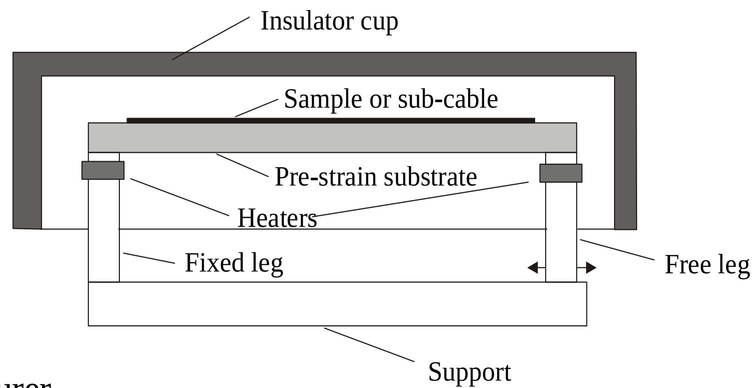
Characterization of pre-strain and multi-dimensional deformation influences on strands and sub-cables

University of Twente

<u>Experiments and analysis that might answer those questions:</u>

- Pre-strain measurements on strands and sub-cables using Tc => Not accurate on standard barrel



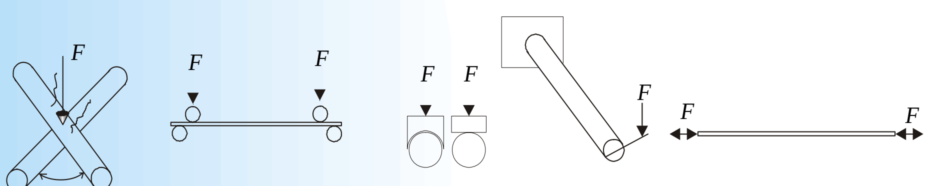


On strands => Delivers Tc(defined pre-strain) / manufacturer

On separate strands in sub-cable => Delivers Tc(pre-strain sub-cable)

Correlations?

- Principal deformation experiments on short strands + calculations



Strand x strand | Bending | Transverse pressure | Torsion | Uni-axial

Delivers:

Dominating load
Basic understanding
Calculations vs experimental

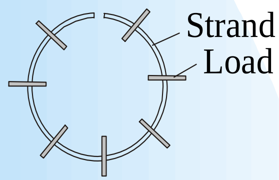
A. Godeke January 2001

Characterization of pre-strain and multi-dimensional deformation influences on strands and sub-cables

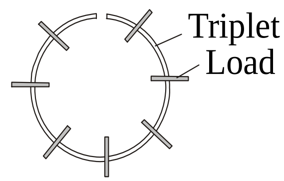
University of Twente

Upgrading of short sample experiments to long strand and sub-cable level

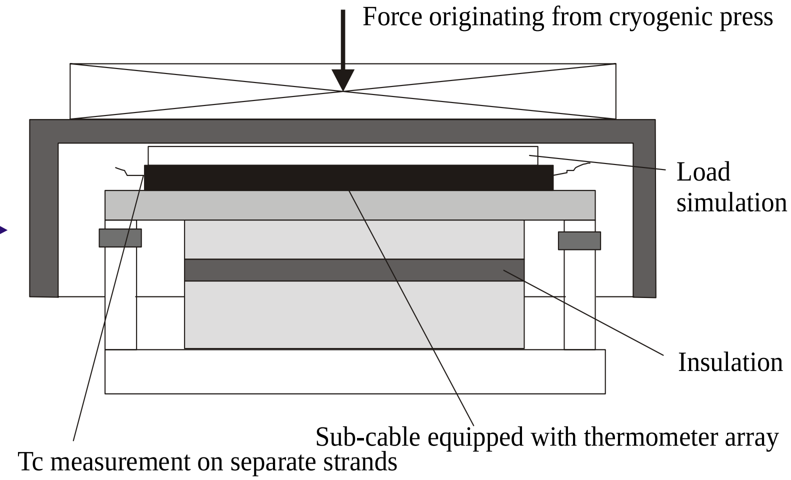
Short sample results



Multiple load experiment



Multiple load on triplet



Sub-cable deformation experiment

Delivers to what extend short sample experiments can describe cable deformations

- Extracted strand measurements (Known?) => Delivers influence of production
- Measurement of a witness sample in Twente => Difference because of heat treatment?
- Inter-laboratory comparisons of Twente, JAERI and CEA data and application of the Twente scaling on the complete database => Description with one single parameter set? Differences?

- Detailed measurements and analysis of the RF and NbAl strands (CS insert)
- Include N(B,T) in the scaling relations

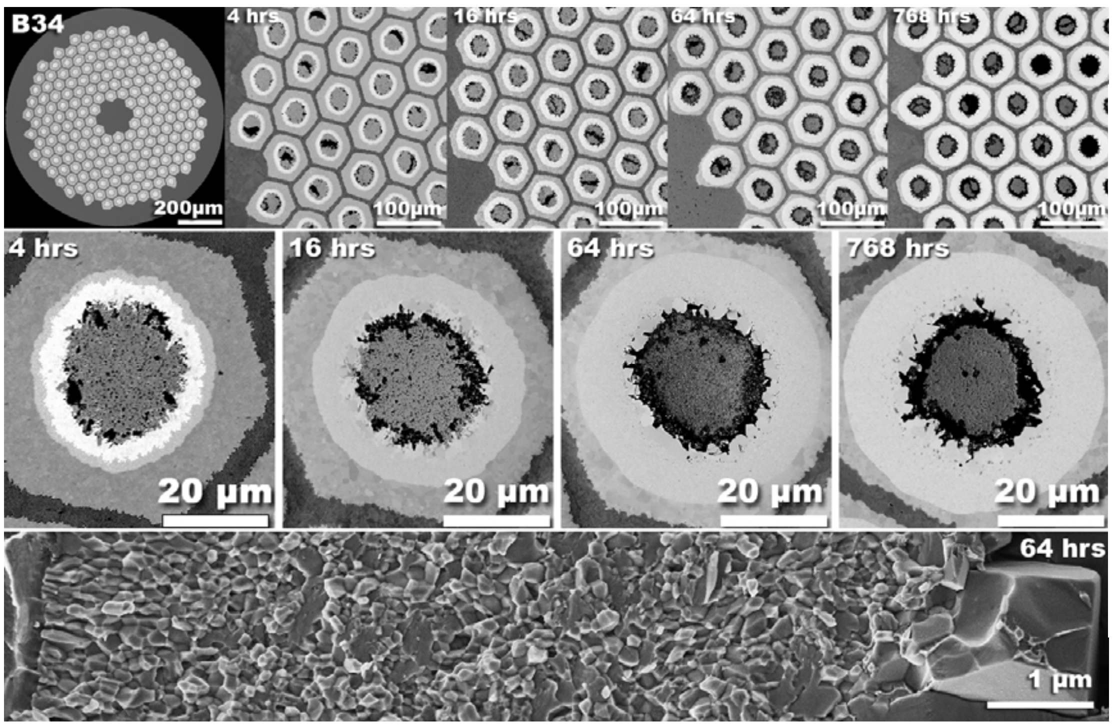
A. Godeke January 2001

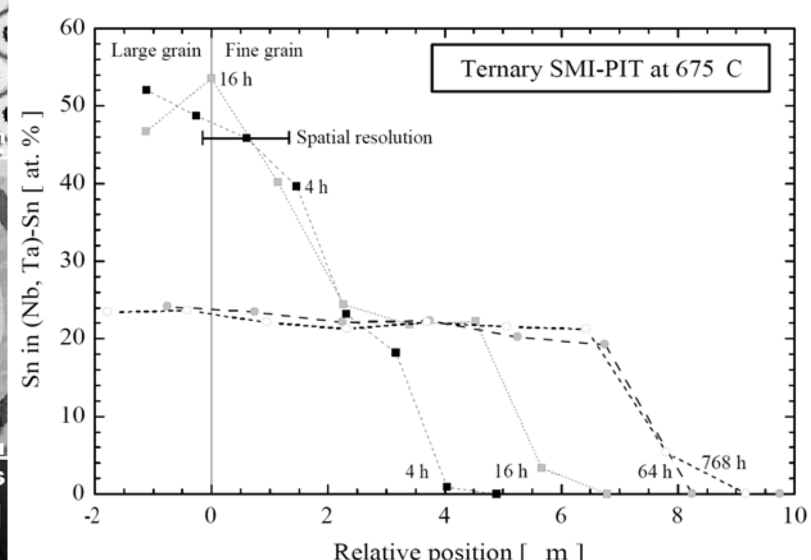
2002: J_c scaling and Material Science

Questions

- What causes tails in Kramer plots?
- Can a better description for $J_c(T)$, i.e. $H_{c2}(T)$ be found?

Answers: What is inside a wire?





Wires have compositional gradients

SMI-Powder-in-Tube wire

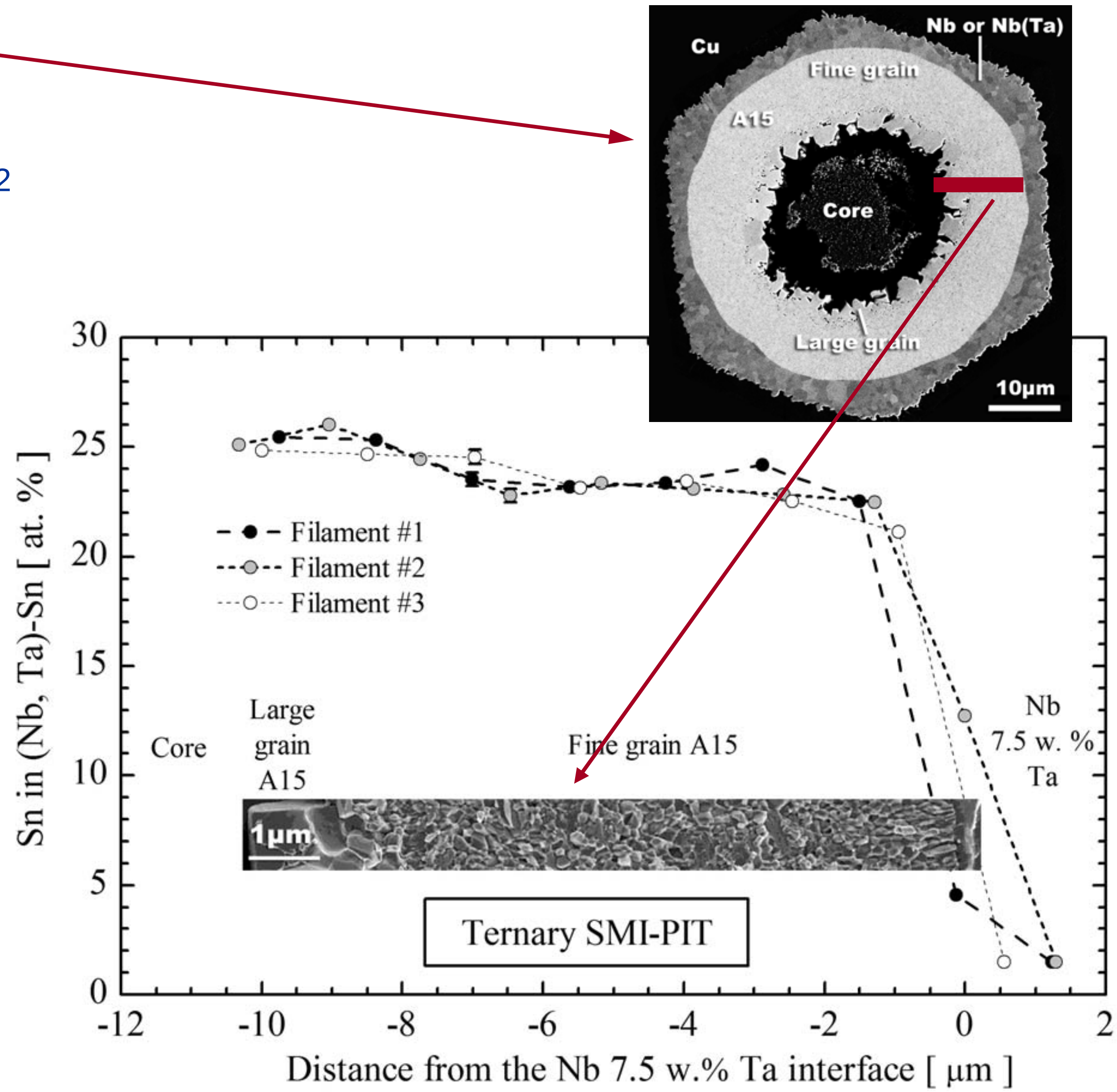
- 0.3 at.% Sn/μm
- J_c(12T,4.2K) = 2250 A/mm^2

Geneva Bronze route wire

- 4 at.% Sn/μm
- J_c(12T,4.2K) = 720 A/mm^2

OST Internal Sn

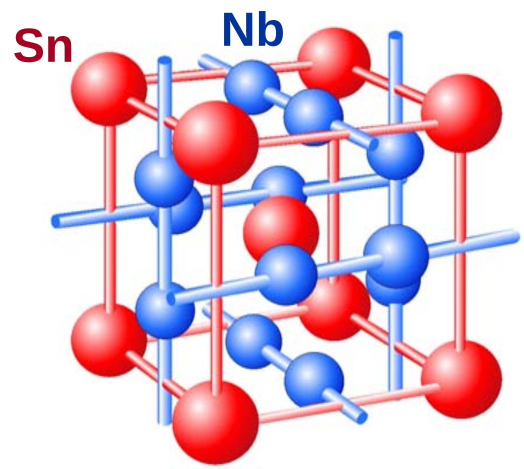
- Flat Sn content: ~24 at.%
- J_c(12T,4.2K) = 3000 A/mm^2



What do Sn gradients do?

In general

- Sn deficiency
- Tetragonal distortion
  - 24.5 – 25 at.% Sn
- Strain
- Alloying (Ti, Ta, …)
- Dislocations
- Anti-site disorder

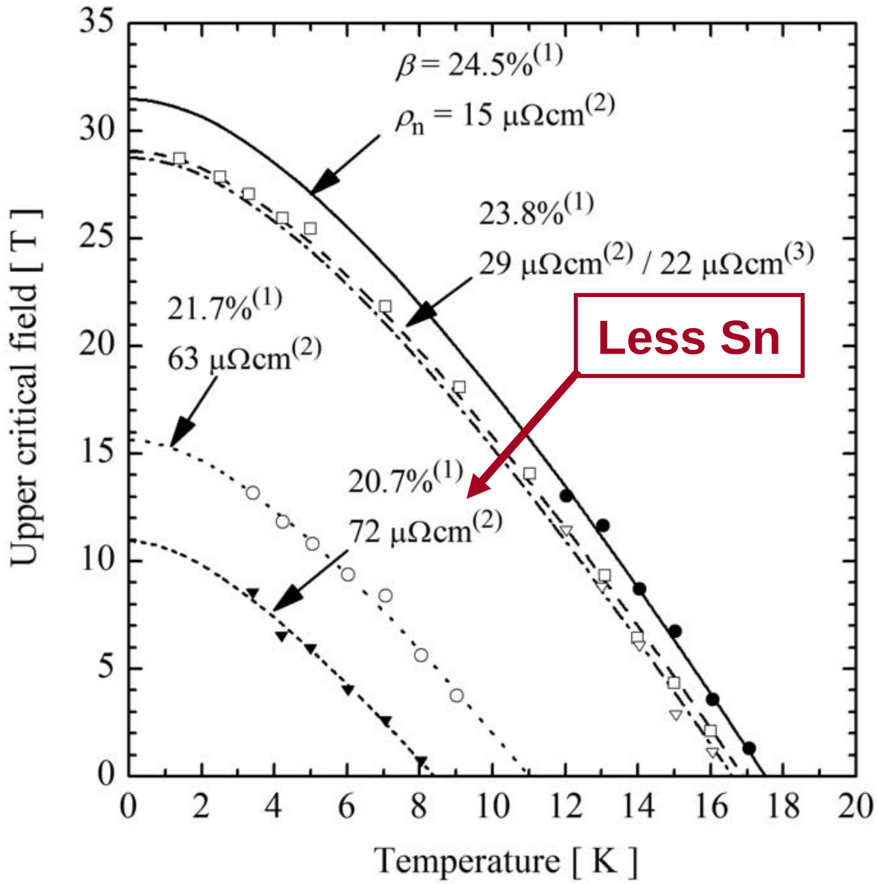


All affect Nb chain integrity (‘Long Range Order’)

- And thus $N(E_F)$ and λ_{ep}
- And thus T_c and H_{c2}

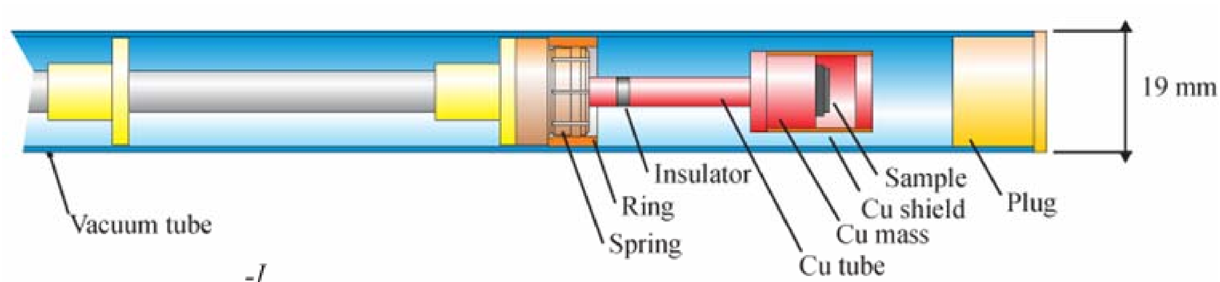
$H_{c2}(T)$ versus Sn content

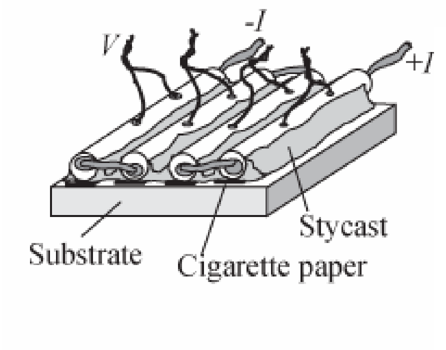
- Sn richer Nb-Sn has higher $H_{c2}(T)$ (until ~ 24.5 at.% Sn)

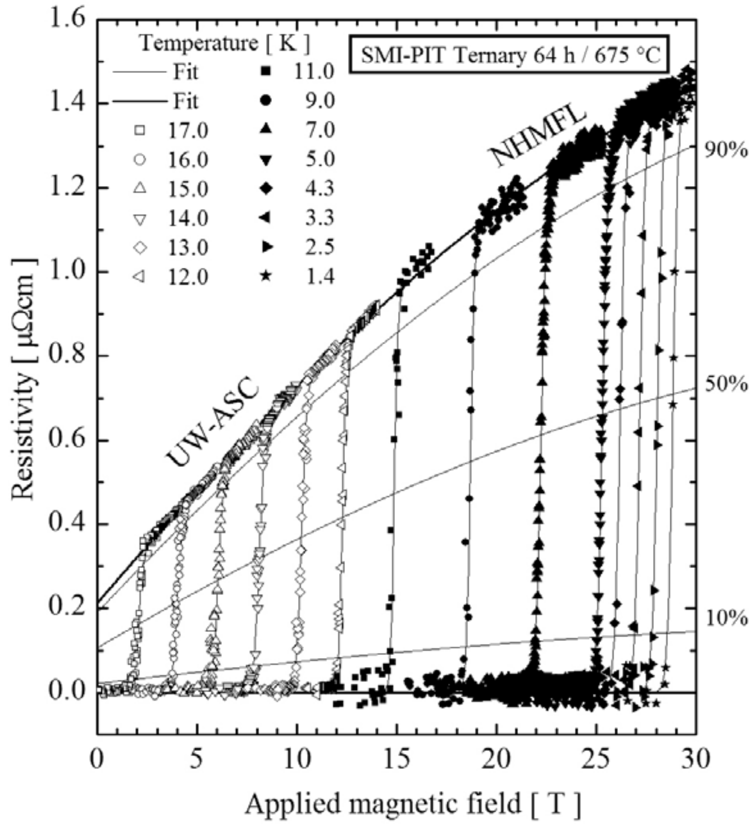


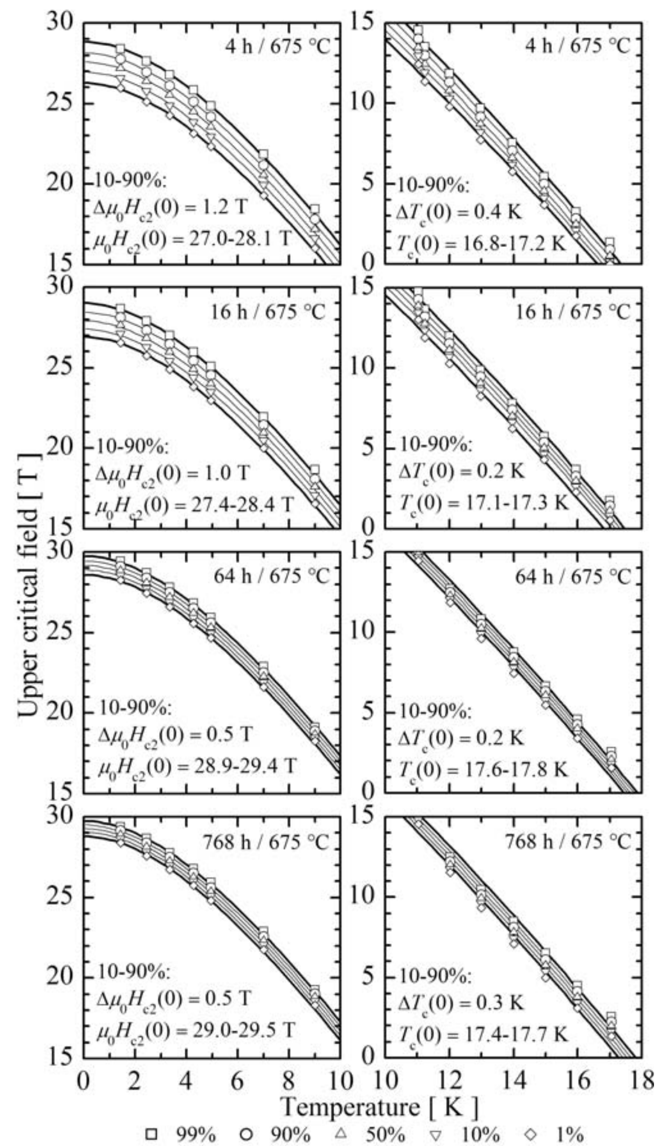
Source:
Jewell, Godeke, Lee, Larbalestier, *ACE* 2004

Measurements of $H_{c2}(T)$ in wires



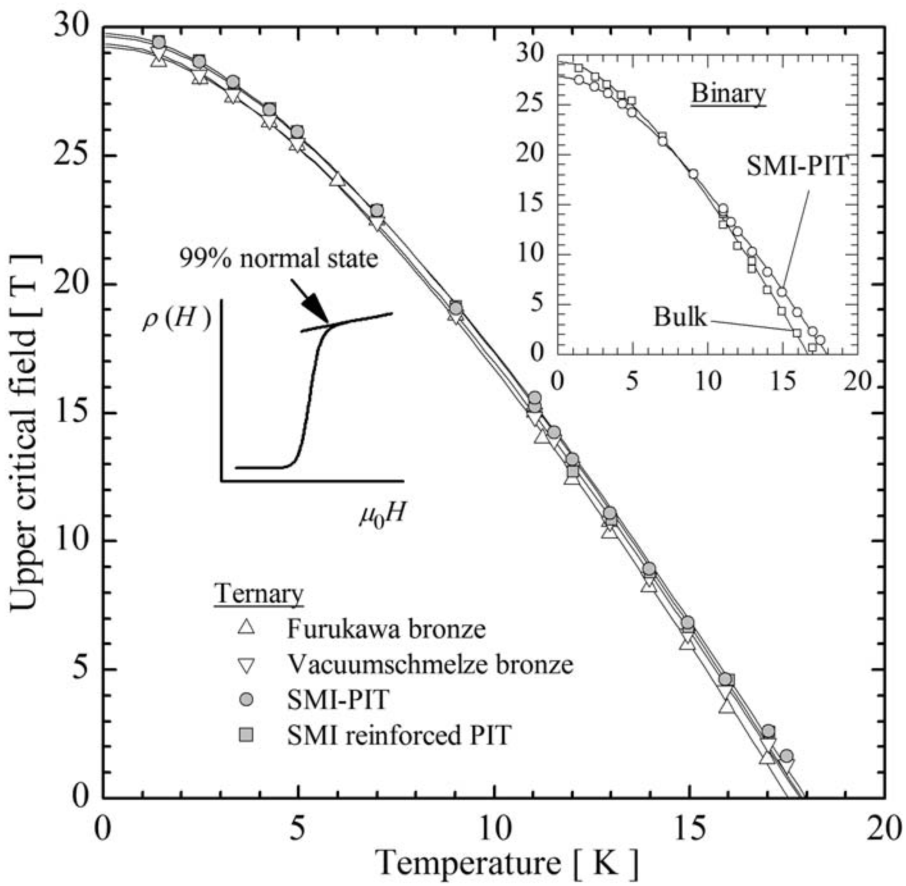






Highest $H_{c2}(T)$ in wires

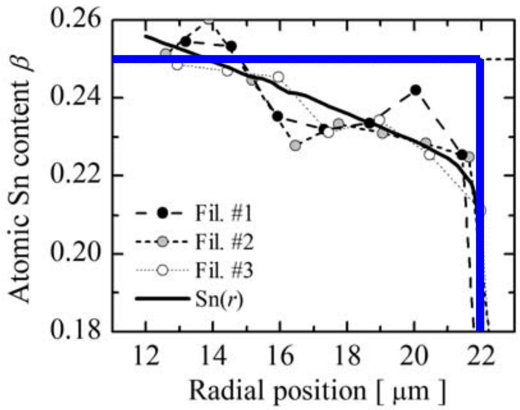
- $\mu_0 H_{c2}(0)$ = 30 T, $T_c(0)$ = 18 K is upper limit

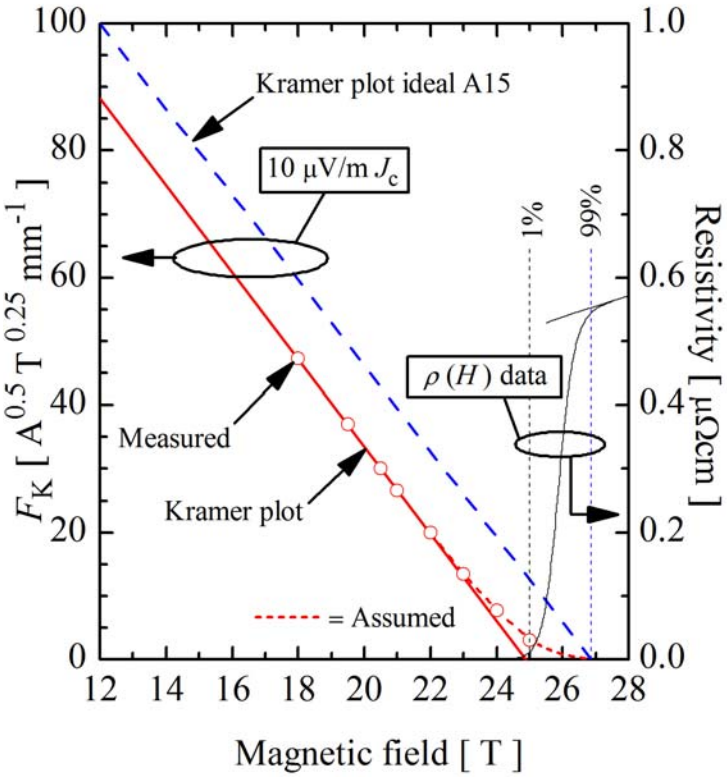


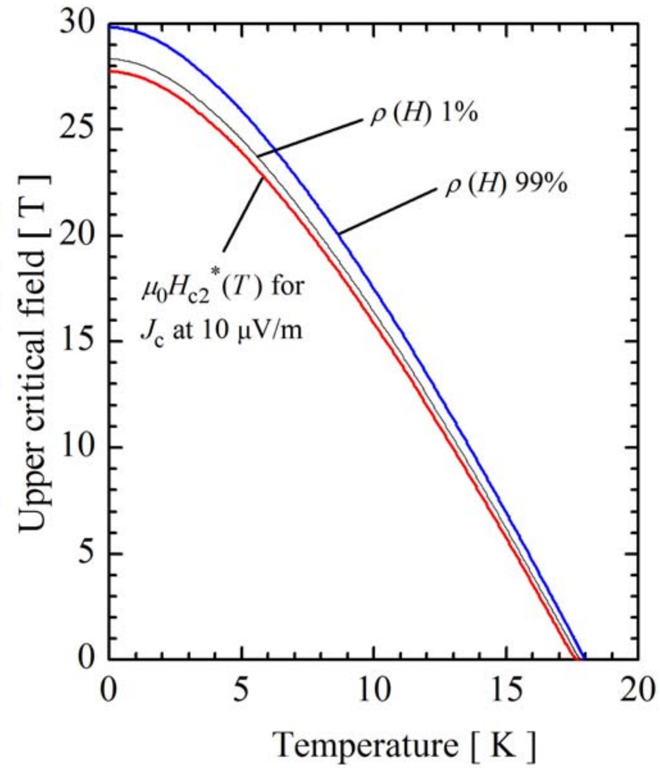
Effective $H_{c2}(T)$* for J_c

J_c scales with 'some' compositional averaged $H_{c2}(T)$*

- Tails in Kramer plots arise through compositional averaging
- J_c gain if all Nb-Sn is stoichiometric?



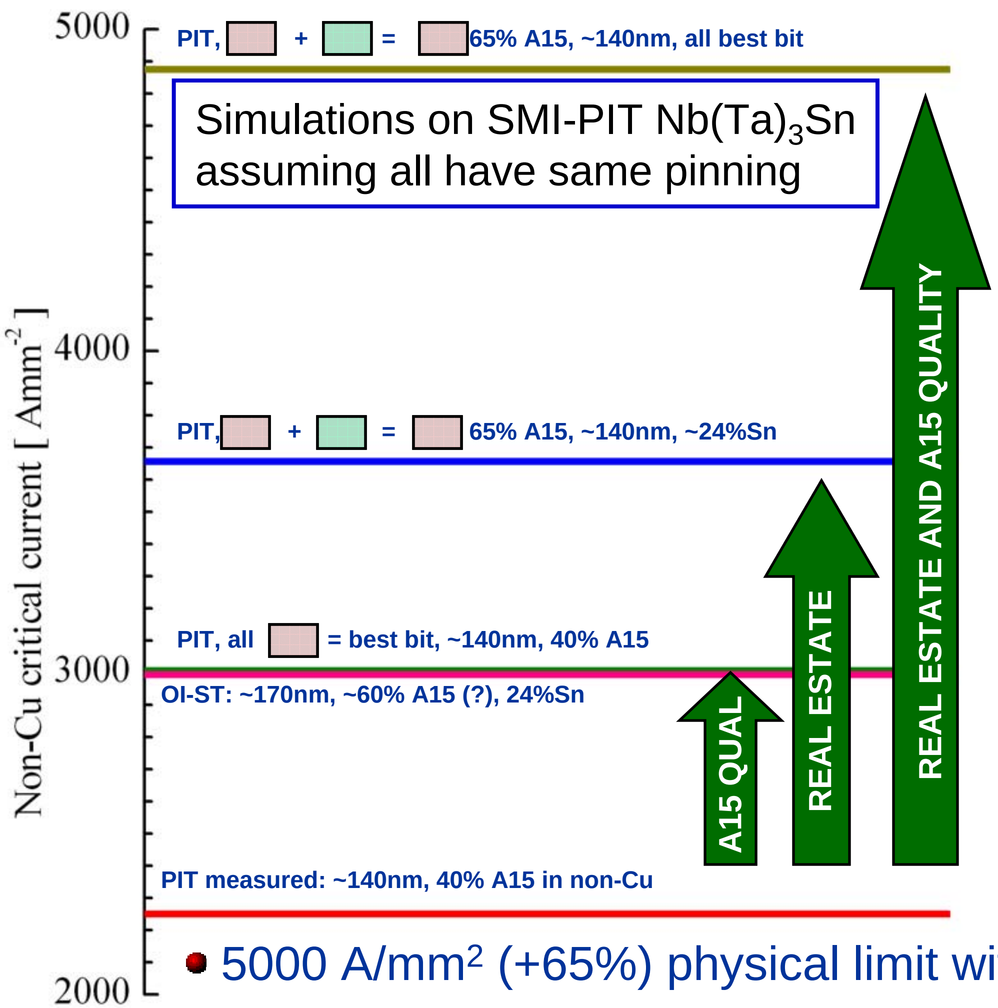


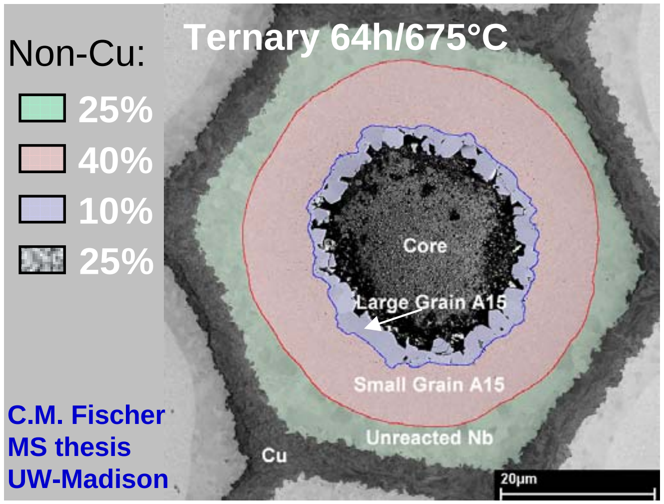


J_c(12T,4.2K)

- From 2250 A/mm^2 to 2900 A/mm^2

Prospects for critical current density

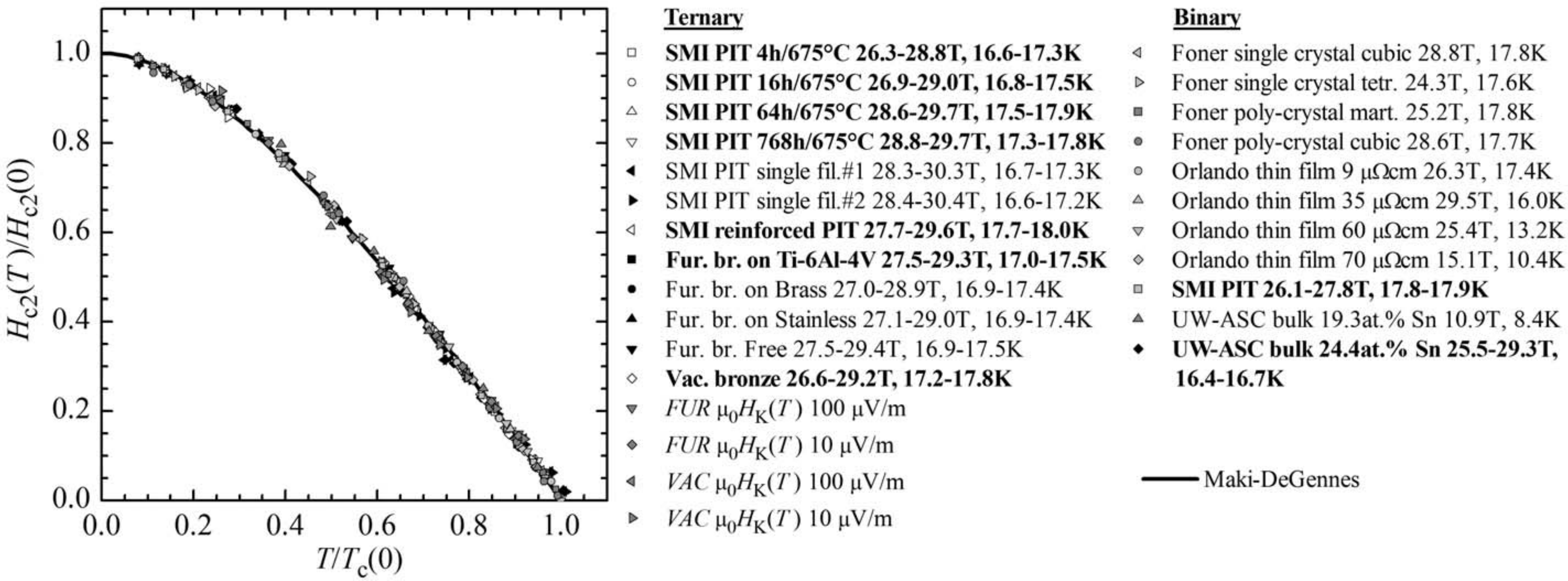




- 5000 A/mm^2 (+65%) physical limit with present wire designs?
  - Unless pinning is improved
- 4000 A/mm^2 realistic optimization goal?

Normalized $H_{c2}(T)$ all available results

- Wires (transport I_c and resistive), bulk, thin film, single crystal



- Shape $H_{c2}(T)$ independent of
  - Composition
  - Morphology
  - Strain state
  - Applied critical state criterion

$$\ln\left(\frac{T}{T_c(0)}\right) = \psi\left(\frac{1}{2}\right) - \psi\left(\frac{1}{2} + \frac{\hbar D \mu_0 H_{c2}(T)}{2\phi_0 k_B T}\right)$$

Approximation:

$$\frac{H_{c2}(t)}{H_{c2}(0)} \cong 1 - t^{1.52}, \quad t = \frac{T}{T_c(0)}$$

J_c scaling and Material Science

Questions and answers

- What causes tails in Kramer plots?
  - Compositional averaging of $H_{c2}(T)$ yielding *effective* $H_{c2}^*(T)$ that determines J_c
- Can a better description for $J_c(T)$, i.e. $H_{c2}(T)$ be found?
  - Yes:

$$\ln\left(\frac{T}{T_c(0)}\right)=\psi\left(\frac{1}{2}\right)-\psi\left(\frac{1}{2}+\frac{\hbar D\mu_0 H_{c2}(T)}{2\phi_0 k_B T}\right)$$

Approximation:

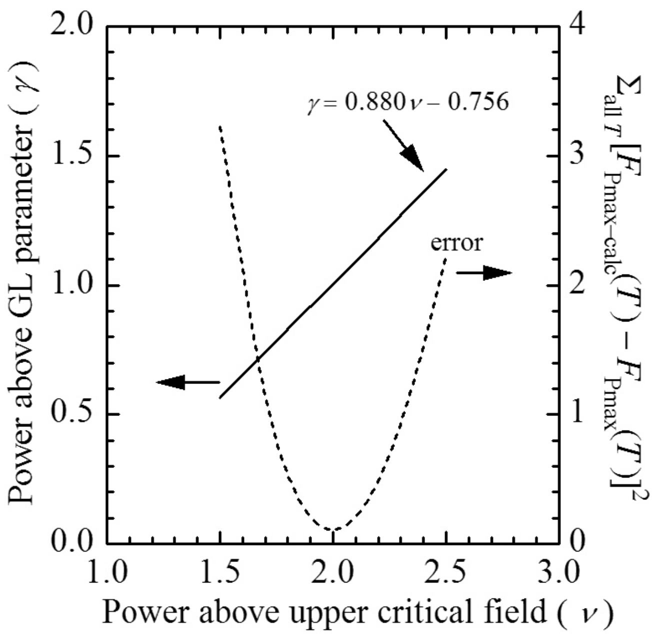
$$\frac{H_{c2}(t)}{H_{c2}(0)}\cong 1-t^{1.52},\quad t=\frac{T}{T_c(0)}$$

  - $H_{c2}(T)$ known, $H_c(T)$ = known ➔ $\kappa(T) = H_{c2}(T)/\sqrt{2}H_c(T)$ known

J_c scaling and known $H_{c2}(T)$

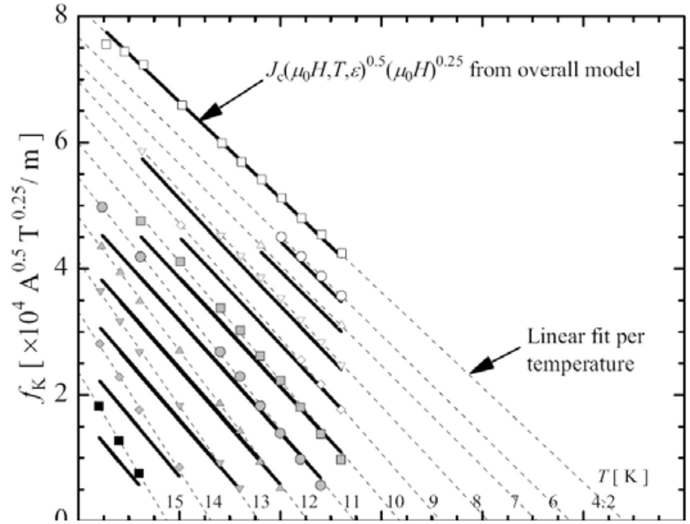
Fitting the powers:

$$F_p(H,T) \cong C\frac{[\mu_0 H_{c2}(T)]^{\nu}}{\kappa_1(T)^{\gamma}} f(h)$$

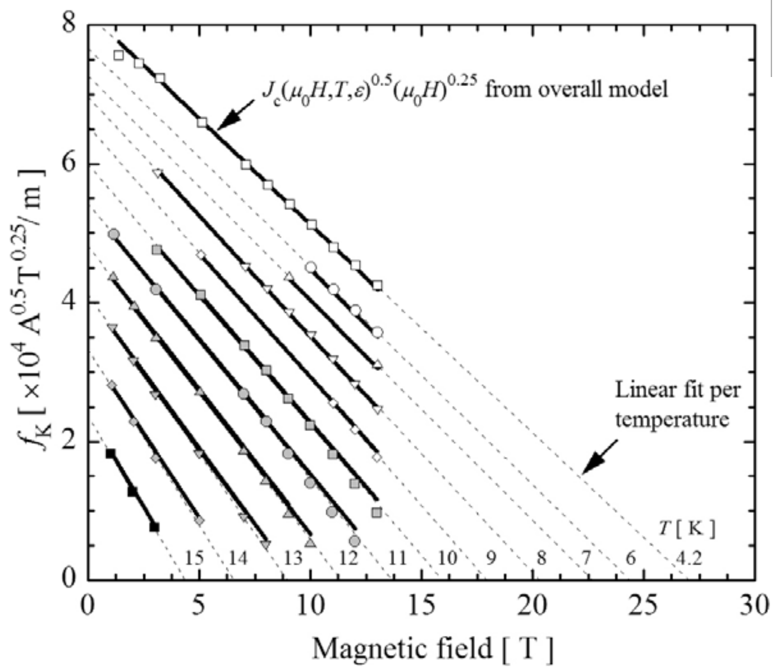


- *T* dependence C66 by Labusch needs revisiting

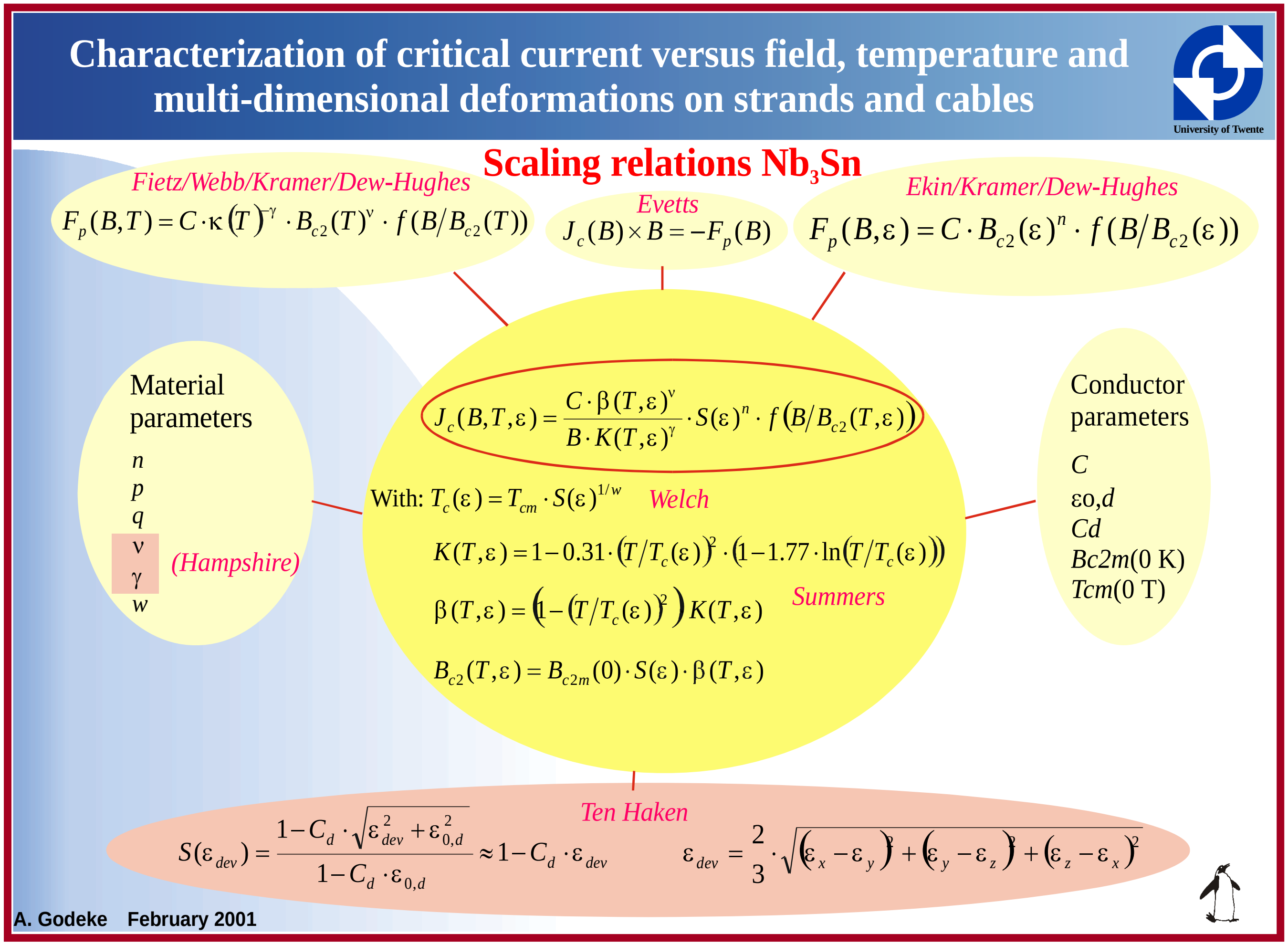
Before



After



J_c scaling and known T dependence



strain temperature field

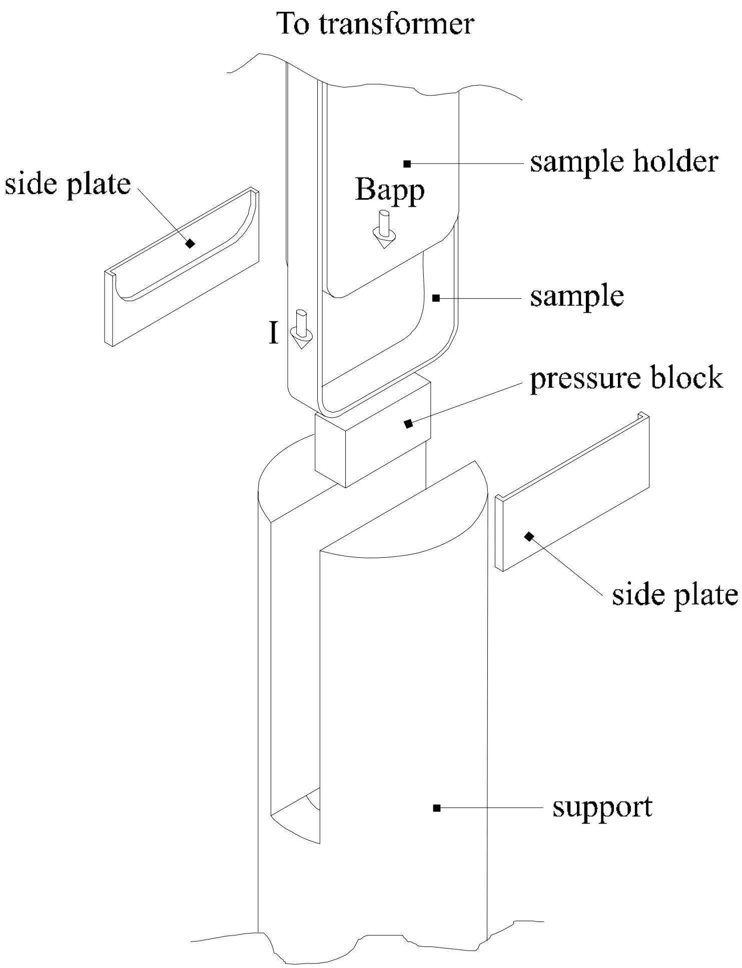
- $J_c(B,T,\varepsilon) = (C/B)\ s(\varepsilon)\ (1-t^{1.52})(1-t^2)\ b^{0.5}(1-b)^2$

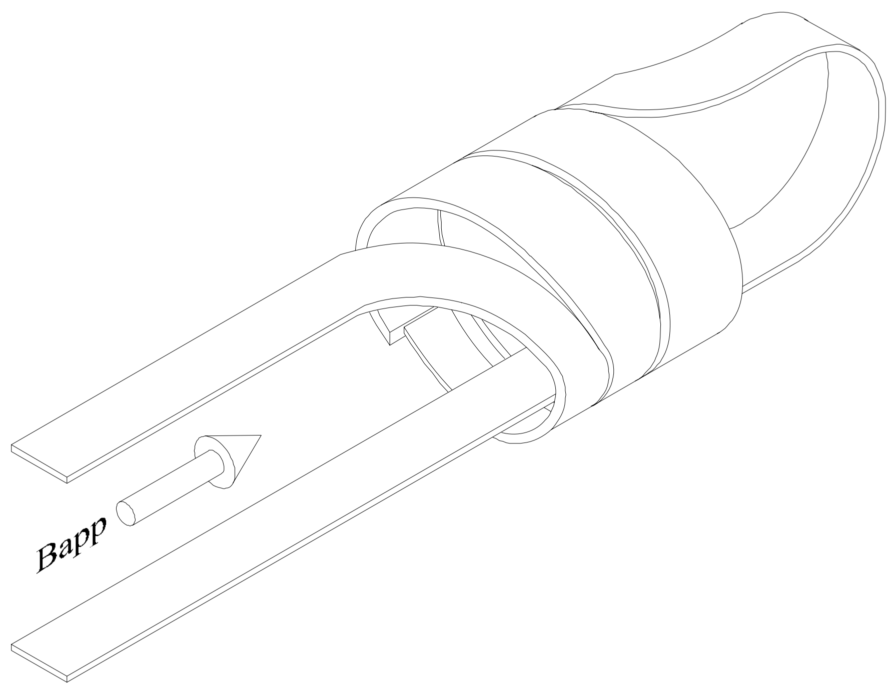
1993 – 1996

Rutherford-type cable characterizations

1993–1995: Cable characterizations

$I_c(F_{\perp},H)$ or $I_c(H)$ with SC transformer, ∅80 mm, 11 T solenoid



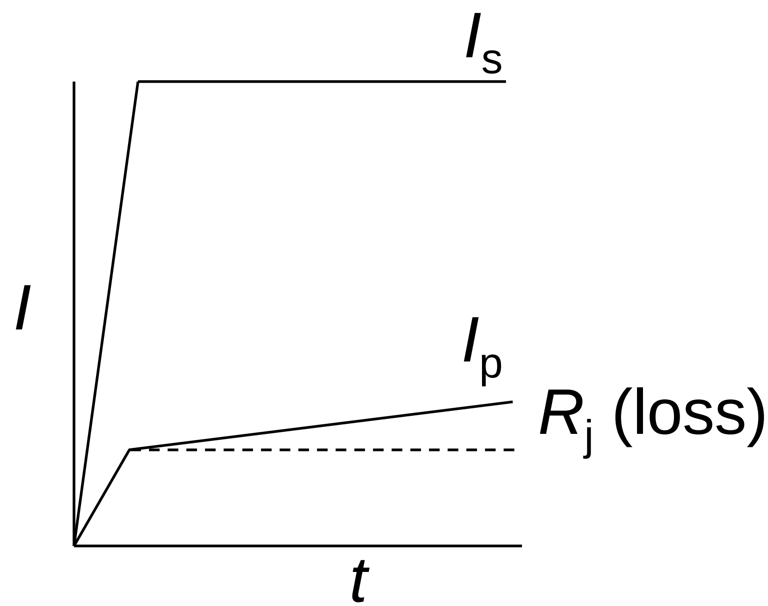


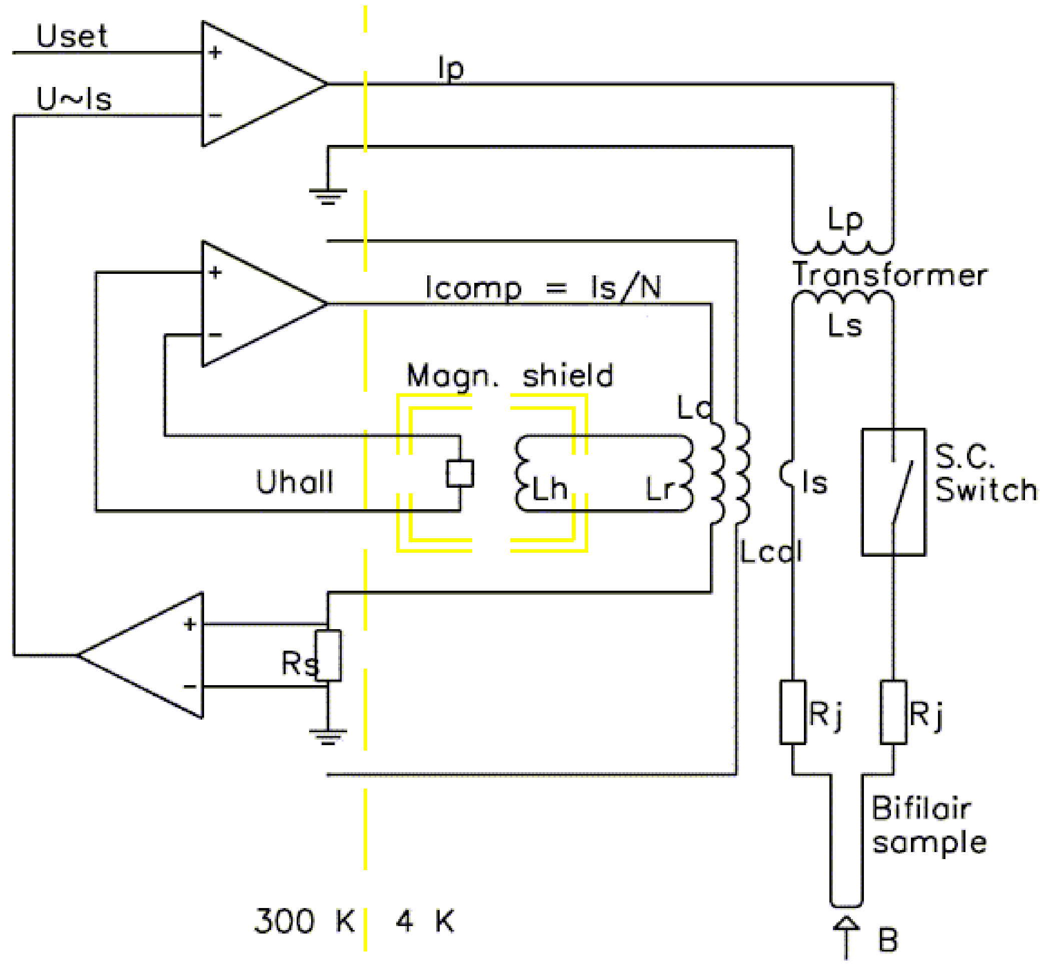
Source:
Godeke, Wessel, Krooshoop, Ten Kate, *Report* 1996

1993–1995: Cable characterizations

SC transformer systems

- Absolute accuracy 1%
- Drift < 0.1%
- Current up to 50 kA
  - MIT version: at 5 kA/s
- Virtually no ripple
  - nV-level measurements





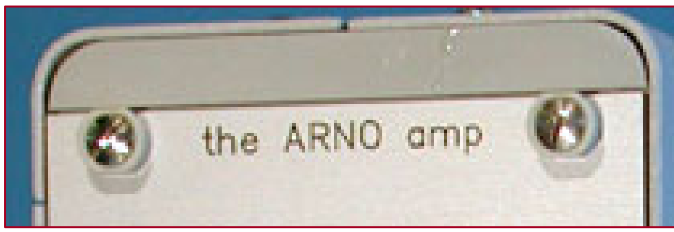
$U_{Lr} \propto dI_s/dt$, $U_{hall} = \int U_{Lr}$

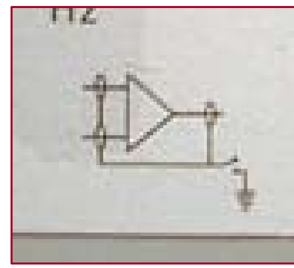
U_{hall} not linear with H_{Lh} ➔ null system

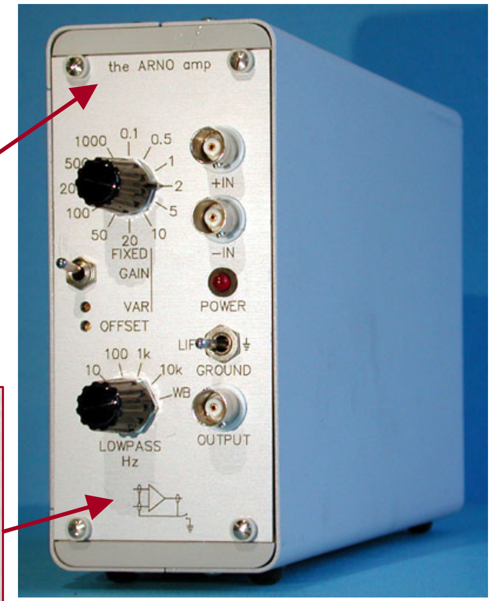
1993–1995: Control unit and spin-off

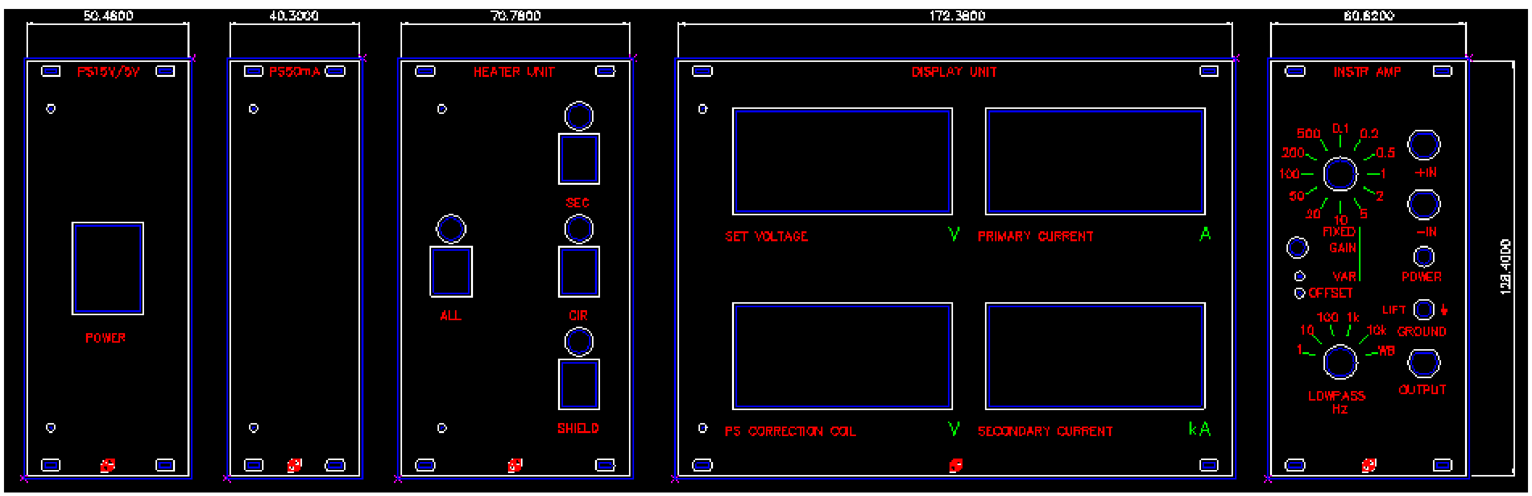
Control unit for SC transformer automation

- Spin off instrumentation amplifier
  - Own internal PS: Fully floating
  - 1 IC and 1 op-amp: simple repair
  - Near commercial: ~35 manufactured





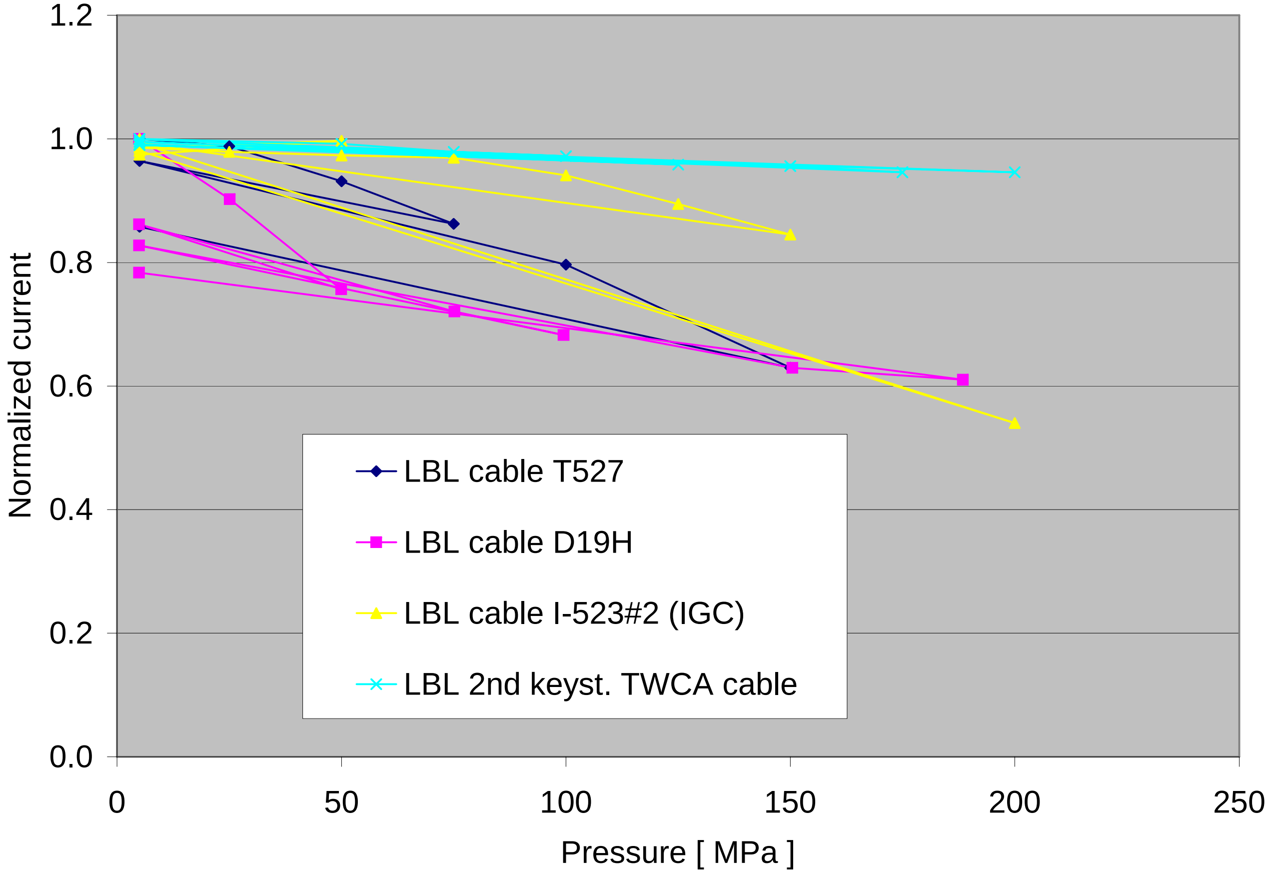




1993–1996: Cable characterizations

‘Some are good, some are not so good…’

- …but D20 worked

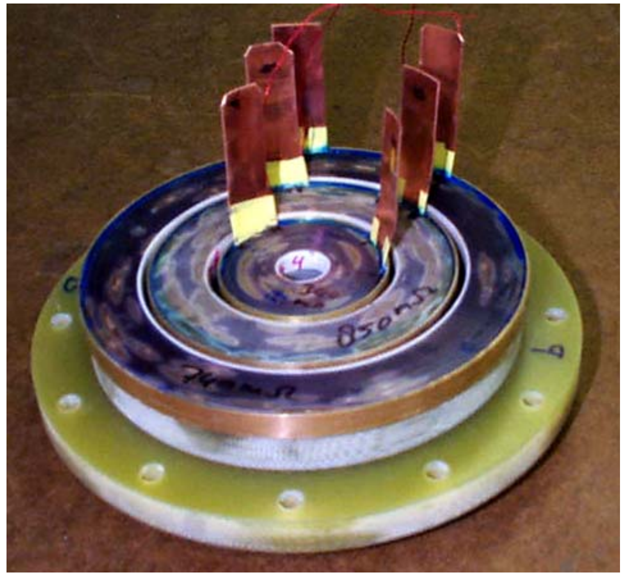


Source:
Godeke, Van Oort, Ten Kate, *Report* 1993
Godeke, unpublished data 1994

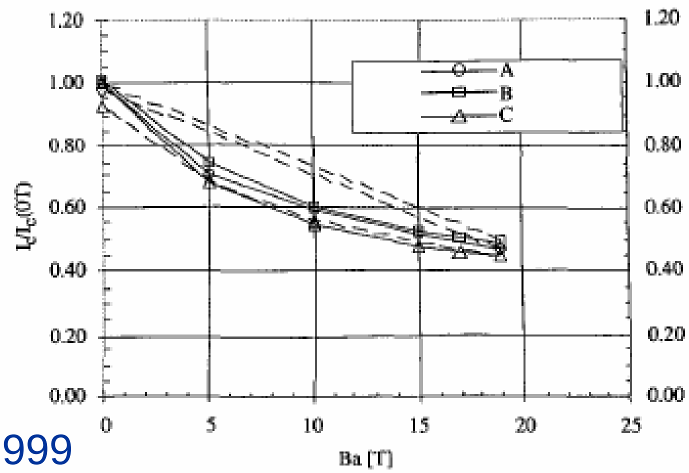
Large scale

1998: 3 T W&R Bi-2212 insert magnet

- Stacked double pancakes
- 3 concentric sections
- Add 3 T in 20 T resistive magnet
- Ceramic sol-gel insulation
- Reaction ~900 C in pure O_2
- Macor inner rings
- Bronze outer support



23 T world record

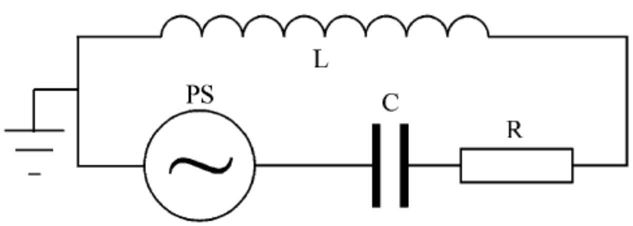


Source:
Weijers,…Godeke,…., *TAS* 1999

1999 – 2001: High *Q*, Bi-2223 AC inductor

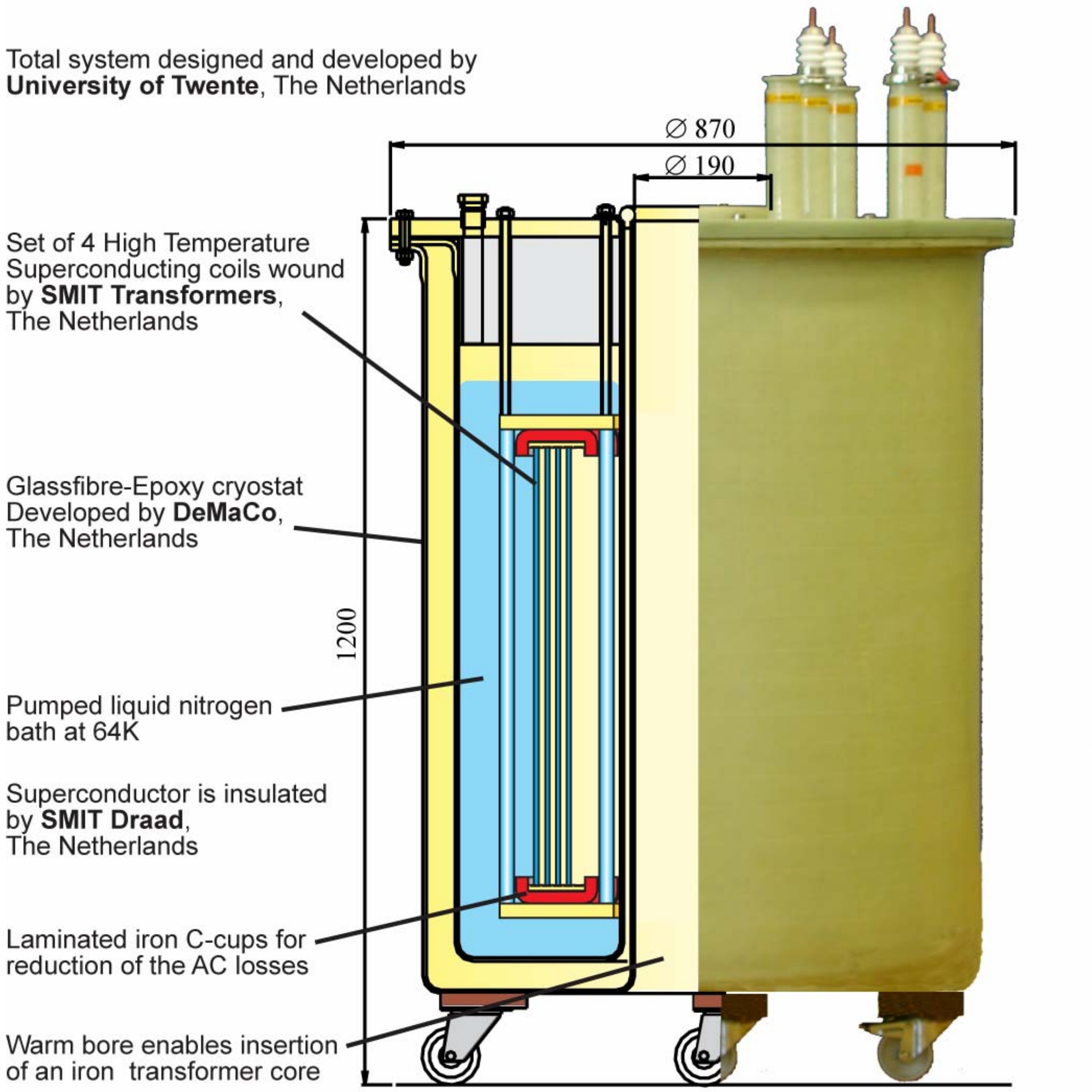
High *V* generator and transformer demo

- 100 A rms
- 10,000 V rms
- 1 MVA rms
- *Q* > 1000



Source:
Godeke, et al., *Phys. C* 2001
Godeke, et al., *TAS* 2001
Shevchenko, Godeke, et al., *TAS* 2001
Godeke, et al., *TAS* 2000
Shevchenko, Godeke, et al., *IOP Conf.* 2000

Schevchenko, PhD thesis 2002
Rabbers, PhD thesis 2001



2000: HV insulation – SC Bi-2223 tapes

Patent:
Godeke, et al., 2001

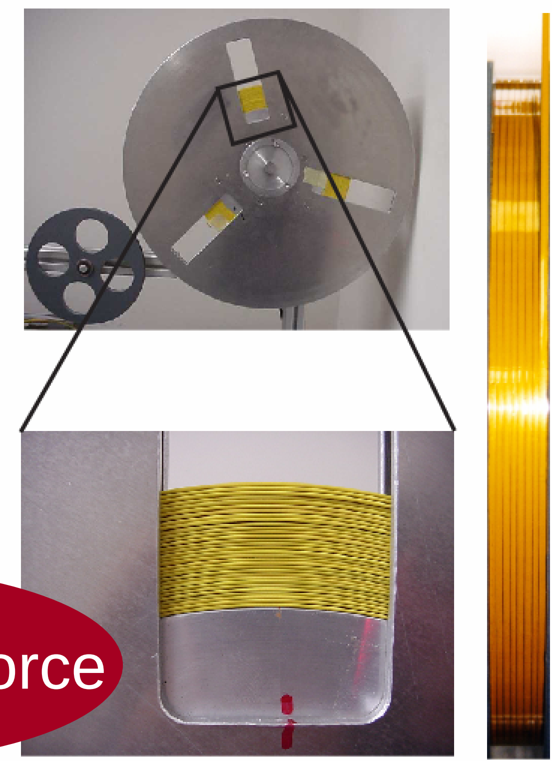
General properties

• Bare tape min. thickness	0.20 mm
• Insulations	Polyimidefilm / Polyesterfilm
• Increase of thickness/width	+0.15/+0.10 mm

SMIT DRAAD

Electrical properties of the insulation

• Breakdown voltage at 300K	
- parallel	min. 6.0kV
- straight in metalshot	min. 4.0kV
• Breakdown voltage at 77K	
- parallel	min. 6.0kV/ min. 5.0kV
- straight with metalfoil	min. 4.0kV/ min. 2.5kV



Mechanical properties of the insulation

• Peel strength at 300K	30 grm/mm
• Adhesion to varnishes	reasonable/ good

Properties of the HTS-tapes after insulation

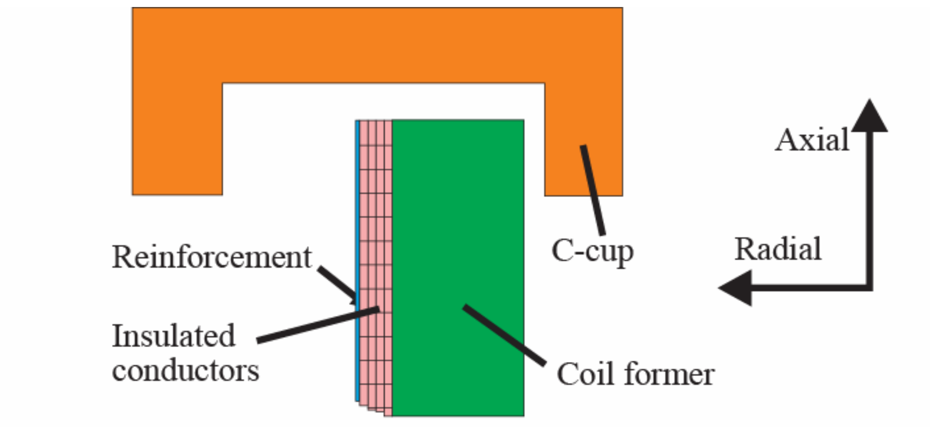
- As conductor without insulation

100 grm max force

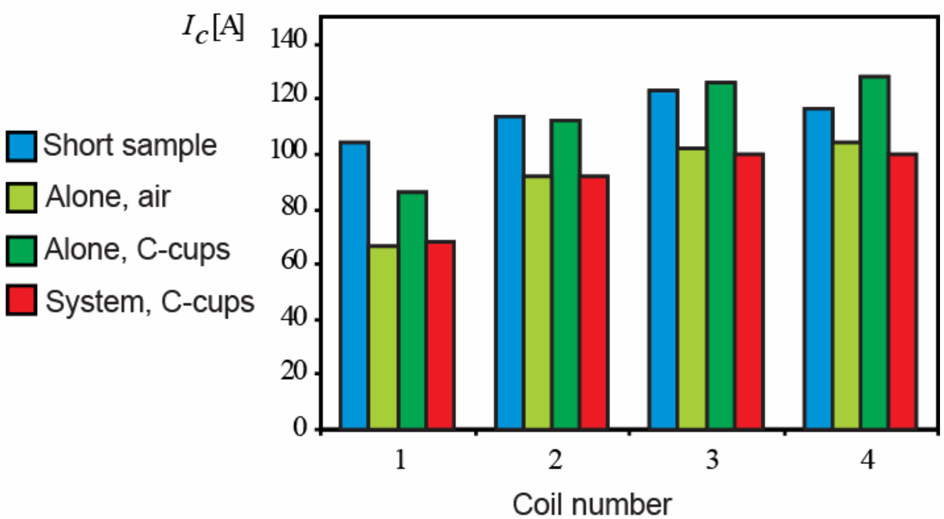
2000: Coil fabrication at SMIT transformers

- 4 coils wet wound at 100 gram tensile load
- Coil manufacturing technology transferred to industry
- All coils manufactured at SMIT Transformer factory

2001: Selected resonator coil results



DC critical current values at 77 K:



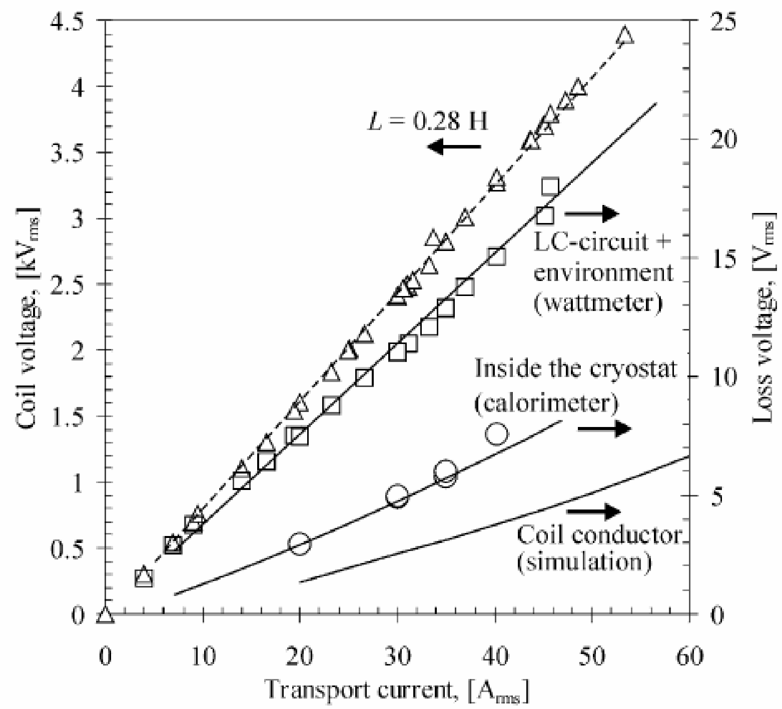
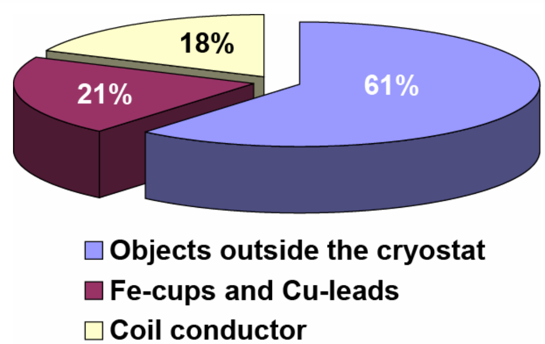
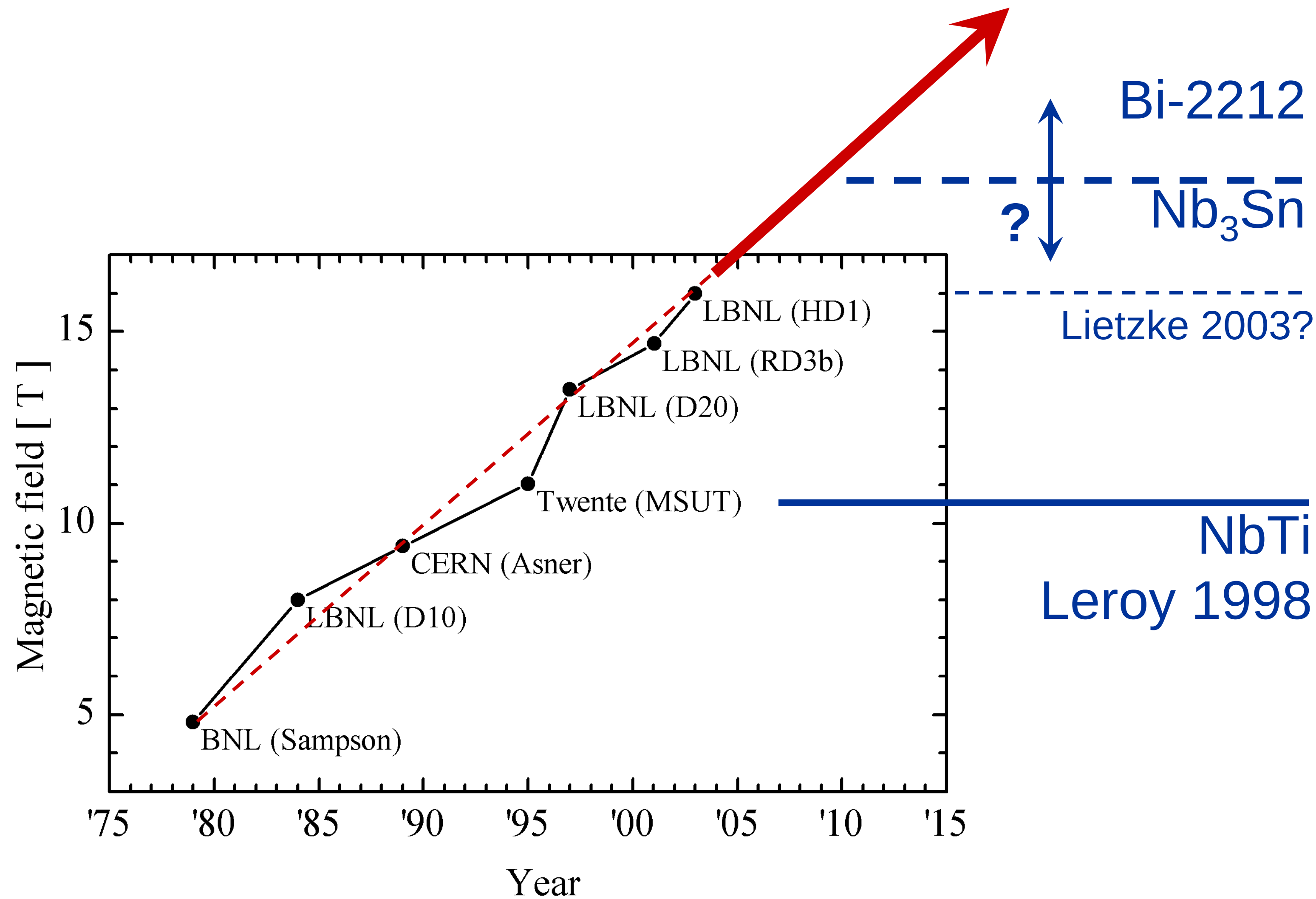


Fig. 3. AC V–I curves of the coil at 77 K and $f = 47$ Hz: the points are measured and the lines are calculated.



2006 – now: Bi-2212 accelerator magnets

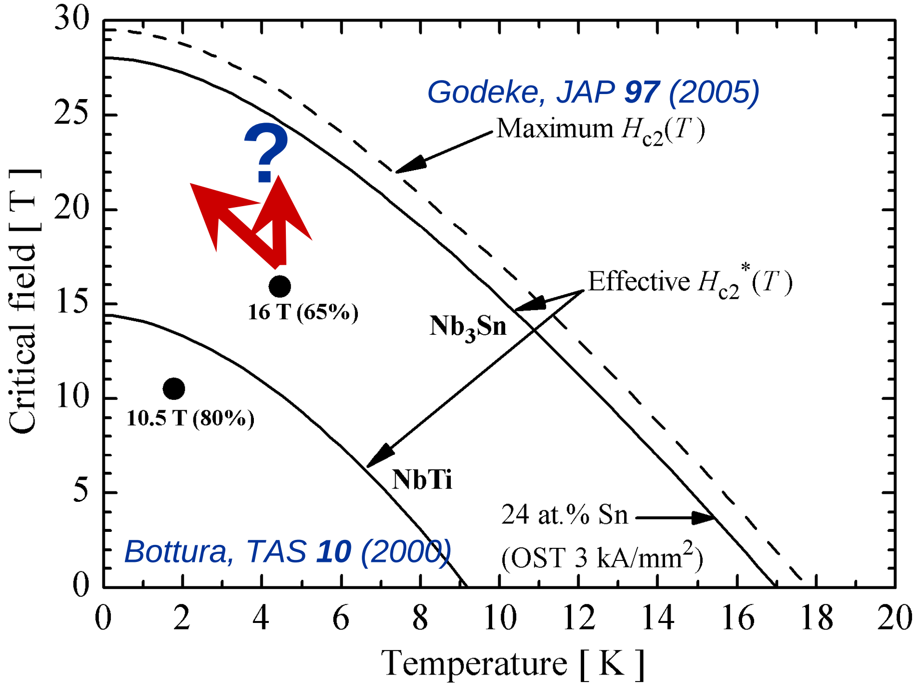
Motivation

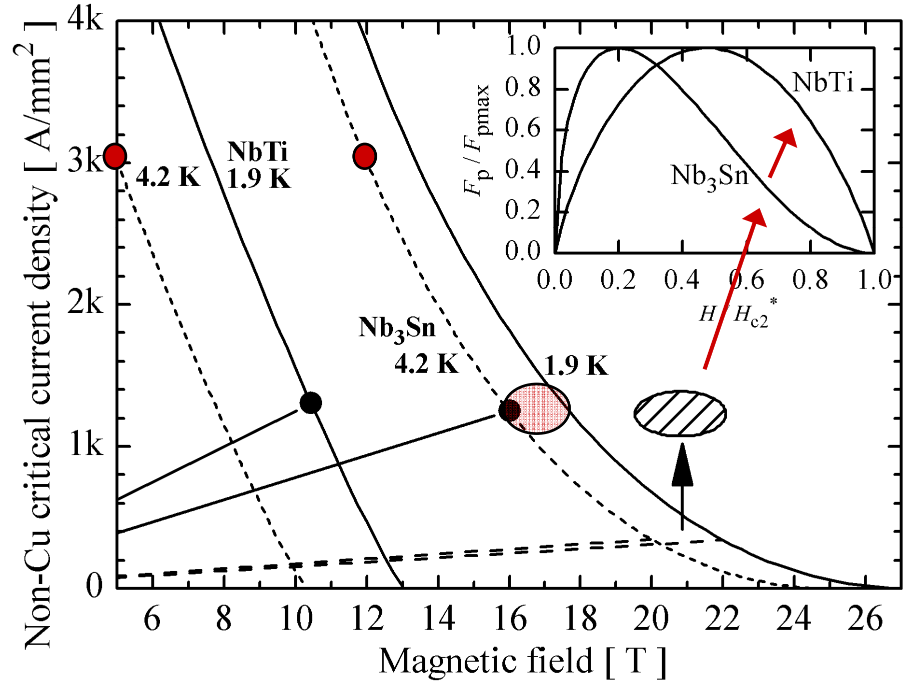


2006 – now: Bi-2212 accelerator magnets

- Nb_3Sn dipoles are limited to 17 – 18 T

NbTi: *Bottura, TAS **10** (2000)*
Nb_3Sn: *Godeke, SuST Oct. 2006*

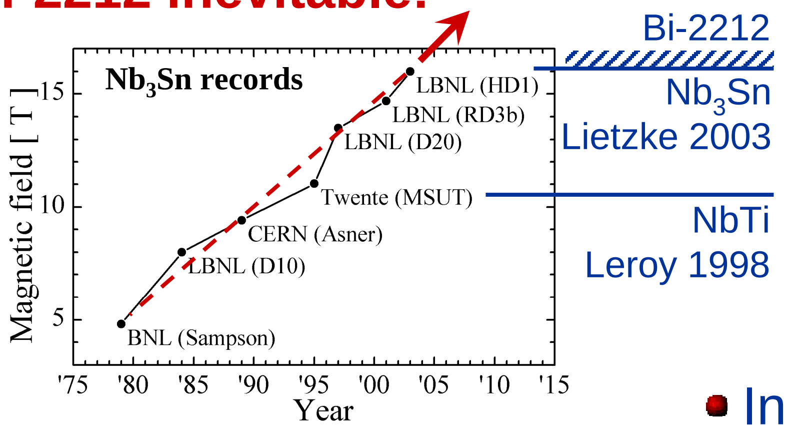




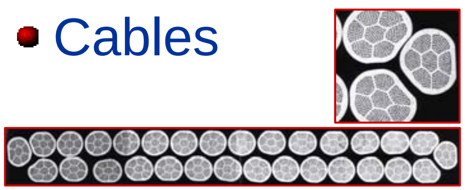
- A switch to Bi-2212 is inevitable: $\mu_0 H_{c2}^*(4.2\ K) \cong 85$ T

Towards new dipole field records

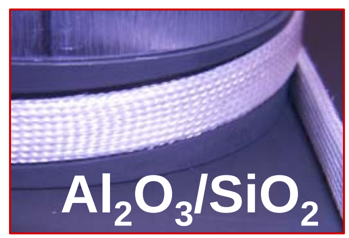
Bi-2212 inevitable!



- Cables



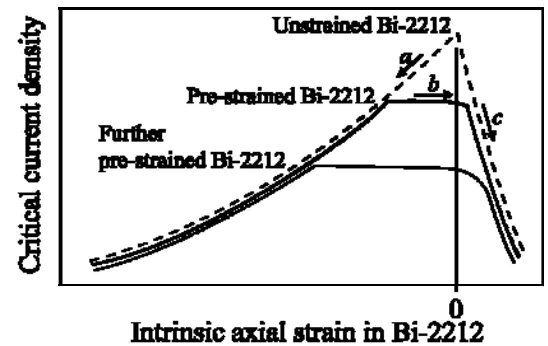
- Insulation



- Challenges ➔ W&R

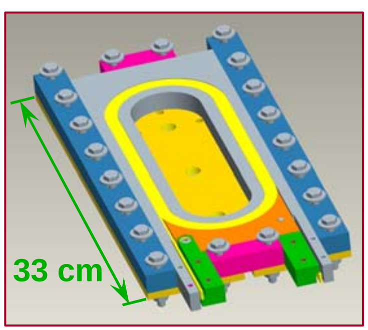
Material	Reaction	Insulation	Quench
NbTi	Ductile R&W	Polyimide	> 20 ms^{-1}
Nb$_3$Sn	675°C Ar/Vacuum	S/R glass	~ 20 ms^{-1}
Bi-2212	890±2°C O_2	Ceramic	< 0.05 ms^{-1}

- Stress / strain

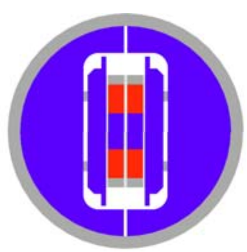


- Irreversible J_c reduction
- 60 MPa limit?

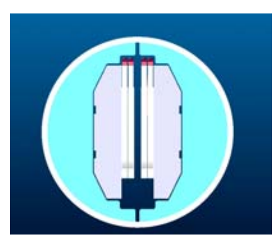
- Modular coils



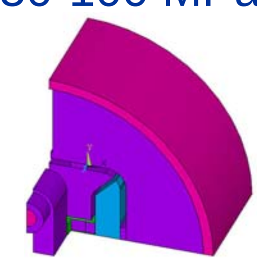
4 T
0-50 MPa

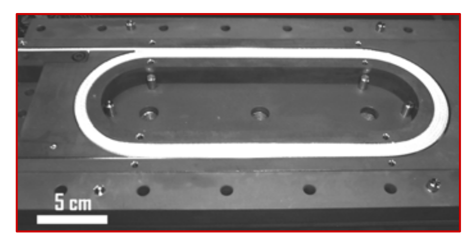


10 T
0-50 MPa



12 T
50-100 MPa





Summary

Combining:

- Novel experiments
- Material Science
- Fundamental Physics
- Superconducting Magnets

Yields:

- Accurate analysis and understanding of performance boundaries
- Suggestions for ways to push these boundaries

- Frontier, record setting superconducting magnet systems
  - ITER, NMR systems, Utility Systems, Accelerator Magnets